



## **APPROACHES TO IMPROVE SUSTAINABILITY IN TEXTILE INDUSTRY**

### **Considerations regarding apparel component development**

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Chemical Engineering, Master's thesis

2025

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Examiner: Professor Rama Layek

Supervisor: Dr Peter Gleeson

## ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Engineering Sciences

Chemical Engineering

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Master's thesis

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72 pages, 18 figures, 6 tables and 8 appendices

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Keywords: Textile fibre, PES fibre manufacturing, PET textile fibre, textile recycling, bio-based PET, biodegradable PET

This study set out to review alternative raw material options for existing textile apparel component(s), heat transfer embellishments for apparel, which could possibly enhance sustainability rating of the component itself and compliment sustainability rating of the garment a component would be applied onto.

As the components in question have PET fibre surface layer and are intended to be heat applied onto PET textile articles, the literature part of the study focused on review of PET fibre, its current part in textile industry and its future prospects. As per literature review findings, both, the use of recycled raw material(s) or/and the unification of raw materials for polyester-based textile article, were confirmed to be worthy targets. Both approaches are thought to enhance PET fibre circularity and allow reduction of fossil based raw materials in PET fibre manufacturing.

The experimental part of the work consisted of assessing possibilities for raw material alternatives. Trials outcomes where existing product components were replaced with selected materials are discussed. Suitability of the alternative raw materials under current processing conditions within the existing manufacturing lines and their impact on product performance in comparison with the existing products was reviewed. This work confirms virgin PET textile can be replaced with recycled PET and PU containing backing layers can be replaced with polyester backing layers without major alterations to existing production lines. This work serves as a starting point for future product sustainability assessments and developments.

## TIIVISTELMA

Lappeenrannan-Lahden teknillinen yliopisto LUT

LUT School of Engineering Sciences

Kemiantekniikka

Tuulia Inkinen

## **KESTÄVÄ KEHITYS TEKSTIILITEOLLISUUDESSA**

### **Askeleita asuste-komponenttien ympäristöystävällisyyden edistämiseksi**

Kemiantekniikan diplomityö

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Avainsanat: Textile fibre, PES fibre manufacturing, PET textile fibre, textile recycling, bio-based PET, biodegradable PET

Tämän työn tavoitteena oli löytää raaka-aine vaihto-ehtoja jo tuotannossa olevien tekstiiliasuste-komponenttien valmistus materiaaleille, jotka mahdollisesti parantaisivat komponenttien (ympäristökuormitusta arvioivaa) kestävyysluokitusta, sekä mahdollisesti täydentäisivät itse tekstiilivaatteen (ympäristökuormitusta arvioivaa) kestävyysluokitusta.

Koska kyseisillä komponenteilla on PET tekstiilikuitu pintakerros ja ne on tuotettu lähinnä PET tekstiiliasusteita varten, työn kirjallinenosa keskittyi PET tekstiilikuituihin, niiden nykyiseen ja tulevaisuuden rooliin tekstiiliteollisuudessa. Kirjallisenosan perusteella sekä kierrätettyjen raaka-ainenden käytön että raaka-aineiden yhdenmukaistamisen todettiin olevan arvokkaita tavoitteita sillä molempien lähestymistapojen ajatellaan yleisesti parantavan PET tekstiilikuitupohjaisten tuotteiden kierrättämistä ja sen kautta mahdollistavan tuotannossa käytettävien fossiilisten raaka-ainenden määrän vähentämistä.

Työn kokeellisessa osassa testattiin valittujen raaka-aine vaihtoehtojen soveltuvuutta nykyisiin tuotantolinjoihin, ilman että tuotantoprosesseja täytyisi merkittävästi muuttaa. Työ toimii lähtökohtana tuleville tuotteiden kestävyuden parannus arvioinnille ja kehitykselle.

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9<sup>th</sup> of June 2025

Tuulia Inkinen

## SYMBOLS AND ABBREVIATIONS

$l$	<i>length</i>	$\mu\text{m}, \text{cm}, \text{mm}, \text{m}$
$M_n$	<i>number average of molar mass</i>	
$M_w$	<i>weight average molar mass</i>	
$M_w/M_n$	<i>molar mass dispersity</i>	
$t$	<i>tonne</i>	$t (= 1000 \text{ kg})$
$T_m$	<i>melting temperature</i>	$^{\circ}\text{C}, \text{K}$
$T_g$	<i>glass transition temperature</i>	$^{\circ}\text{C}, \text{K}$

### *Abbreviations*

$Bt$	<i>Billion tonnes</i>
$CCS$	<i>Carbon capture and storage</i>
$CCUS$	<i>Carbon capture, utilization and storage</i>
$CO_2$	<i>Carbon dioxide</i>
$CPA$	<i>Caligo Printers Association</i>
$D$	<i>Denier</i>
$DC$	<i>Dimensional change</i>
$DMT$	<i>Dimethyl terephthalate</i>
$DP$	<i>Degree of polymerization</i>
$DPP$	<i>Digital product passport</i>
$EG$	<i>Ethylene glycol</i>
$EOR$	<i>Enhanced oil recovery</i>
$GRS$	<i>Global Recycled Standard</i>

<i>ICI</i>	<i>British Imperial Chemical Industries</i>
<i>IUPAC</i>	<i>International Union of Pure and Applied Chemistry</i>
<i>MMT</i>	<i>Million metric tonnes</i>
<i>MSW</i>	<i>Municipal Solid Waste</i>
<i>PA</i>	<i>Polyamide</i>
<i>PC</i>	<i>Polycarbonate</i>
<i>PBS</i>	<i>Polybutylene succinate</i>
<i>PBT</i>	<i>Polybutylene terephthalate</i>
<i>PEF</i>	<i>Polyethylene furanoate</i>
<i>PEN</i>	<i>Polyethylene naphthalate</i>
<i>PEO</i>	<i>Polyethylene oxalate</i>
<i>PES</i>	<i>Polyester</i>
<i>PET</i>	<i>Polyethylene terephthalate</i>
<i>PHA</i>	<i>Polyhydroxyalkanoate</i>
<i>PLA</i>	<i>Poly lactide</i>
<i>PTT</i>	<i>Polymethylene terephthalate</i>
<i>PU</i>	<i>Polyurethane</i>
<i>rPET</i>	<i>Recycled PET (Polyethylene terephthalate)</i>
<i>TA</i>	<i>Terephthalic acid</i>

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# 1 Introduction

One of the oldest known records of processed textile fibres (possibly spun and dyed, from Dzudzuana Cave, Georgia) date back to over 30 000 years ago (Kvavadze et al., 2009). Up until almost 125 years ago, all textile fibres in use were natural, plant and animal based (Figure 1). Then the commercialisation of regenerated/man-made natural fibres (e.g. viscose) paved the way for now difficult-to-reverse change in textile fibre manufacturing landscape: invention and commercialisation of *man-made synthetic textile fibres* (Mather, Wardman and Rana, 2023). Today, at the beginning of second quarter of 21st century, two thirds of all textile fibres produced fall under this category (Textile Exchange, 2024 a).

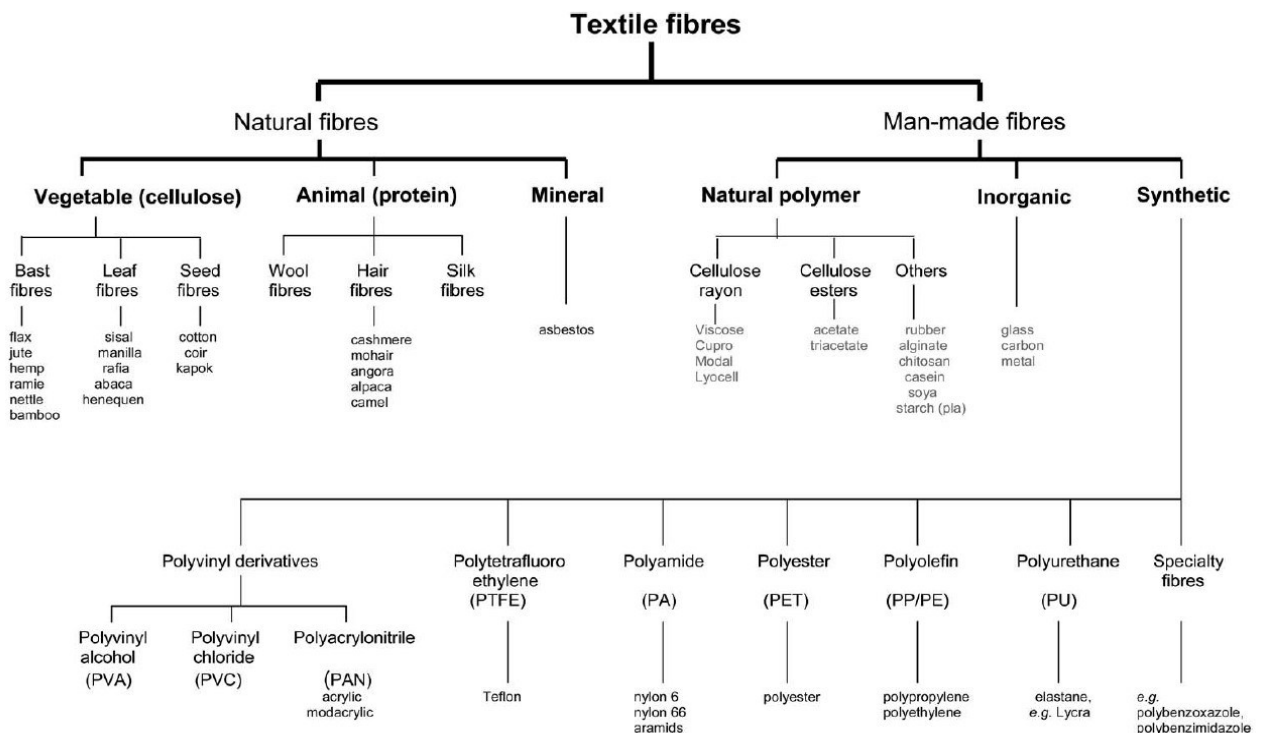


Figure 1. Classification of textile fibres (Mather, Wardman and Rana, 2023)

As with any sector of chemical industry, considerations for environmental pollution controls around textile manufacturing have been in place for number of decades; Reference to textile

mills was included in the US Federal Water Pollution Control Act Amendments of 1972 (US. 86 Stat. 816). Pollution control and pollution reduction requirements extend to both natural and synthetic based fibre processing. At present, textile processing, dyeing and finishing products, is estimated to cause approximately 20% of global unpolluted water contamination (European Parliament, 2024).

In addition to longer-established considerations related to pollution from textile manufacturing, *microplastic pollution*, term which appeared first time in 2004 (at the time used to describe fragments of plastic with both fibrous and granular nature, with dimension of approximately 20  $\mu\text{m}$  (Schmid, Cozzarini, and Zambello, 2021)), is raising increasing concerns.

Synthetic fibres significantly contribute to microplastic and nanoplastic (sized 0.001 - 5 mm and  $< 0.001$  mm, respectively) pollution. According to Manshoven et al. (2022) estimated 8% of annual primary microplastics release to global environment originate from washing of textiles alone. Textiles based on natural origin (whether from man-made semi-synthetic natural polymers or natural fibres) contribute to *microfibre* pollution and all textiles, regardless of fibre type, may contain other contributors to microplastics pollution such as buttons, prints etc. Additionally, although natural fibres, such as cotton and silk, when released into environment, are thought to decompose relatively fast in comparison to man-made fibres, if the fibres have been subjected to processes involving hazardous substances during their manufacturing, the processed natural microfibres can then function as a carrier and their faster degradation rate may lead to expedited leaching of these hazardous substances into the surrounding environment (Cesa et al., 2020; Manshoven et al., 2022).

Although omnipresence of microplastic pollution has been well established, e.g. microplastic fibres have been found in Arctic ice, in bottled water and in ocean floor sediments, the long-term effects on human health and ecosystems remain unclear (Manshoven et al., 2022).

According to Biswas et al (2024), as well as textile and fashion industries having significant adverse environmental impacts and being considered as one of the most polluting industries globally, textile and fashion industries are also the source of estimated 8–10% of global carbon dioxide (CO<sub>2</sub>) emissions annually (Biswas et al., 2024) and emphasis on carbon footprint reduction, for example in a form of waste reduction (both pre- and post-consumer),

and via aim for more circular product life cycle, ought to be considered at every step of design and manufacturing of textile products. To move this approach forward, all components of textile-based products need to be considered. It is these considerations which outline the premises of this work.

Elms Marketing Ireland Ltd (from here on referred to as Elms Marketing) manufactures embellishments for textile apparel industry from various combinations of raw materials (poly(ethylene terephthalate) (PET), poly(amide) (PA), poly(urethane) (PU), silicone etc.). The aim of this project, while maintaining same product performance characteristics, is to find and assess possibilities for more sustainable option(s) for current product(s).

As Loo, Yu and Hu (2023) outline, difficulties encountered in processing heterogeneous waste streams present a significant challenge in textile products recycling, and multi-material fibre compositions currently form a significant part of these obstacles (Loo, Yu and Hu, 2023). One approach to improve sustainability is unification of raw material components for ease of recycling/upcycling of manufacturing waste and the final apparel of which an embellishment is a part of. Elms Marketing client base mostly consists of sports garments manufacturers; currently polyester is the most common base textile to which the embellishments are applied onto.

At the time of commencement of this project work, none of Elms Marketing suppliers were in position to offer 100% recycled polyester and/or polyester only (both requests from Elms Marketing client base) fabric/textile adhesive combination for further processing. The literature review of this work aims to review polyester textile and its position in current and future global environment. The experimental part of this work will assess possible options for recycled material/monomaterial construction.

# Literature Review

In 2023, the total global textile production was estimated as 124 million metric tons (MMT) (an increase of nearly 20 MMT from 2018). Approximately 67% (an increase of 3% from 2018) of the total textile fibres produced were synthetic fibres; 85% of the total synthetic fibre production constituted of polyester fibre manufacturing (of which 12.5% was of recycled origin); Other fibres produced were cotton (20%), other natural plant-based fibres (5%), man-made cellulosic 6% (viscose being the major constituent) and animal fibres 1% (Damayanti et al., 2021, Jönsson et al., 2021, Textile Exchange 2024, a).

According to United Nations (2024), estimated 70 million barrels of oil is used each year to make polyester fibre, which in turn approximates to 0.2% of the world annual consumption of oil (Worldometer, 2016)

As a consequence of global population growth, volume of textile fibre demand is anticipated to continue to increase at an estimated 3% per annum until the end of this decade (El Seoud et al., 2020).

Aim of this literature review is to summarize characteristics and uses of textile fibres in general, further assess the specific qualities of polyester, mostly PET, fibres/textiles, their current role and future prospects in textile fibre industry.

Role of textile adhesives in textile industry, specifically with attention to polyester adhesives in apparel industry and the option of polyester textile adhesive recycling together with polyester fibre, is also briefly reviewed.

## 2 Textile fibres

This chapter gives an overview of textile fibre characteristics in general. The chapter describes physical and chemical, (macro)molecular polymeric, nature of textile fibres, and outlines some of the major differences between different fibre types. This chapter also briefly reviews main properties and uses of textile fibres.

## 2.1 Physical Characteristics

From the numerous natural plant and animal based fibrous structures, i.e. molecular assemblies of fibrous elements, filaments or fibres, which together form a structure exhibiting a fine thread-like form with high length to cross-section ratio and ranging from nanoscopic to macroscopic scale in size (Ferreira et al., 2024), the ones which can be converted into yarns (mostly staple fibres, see Figure 2(b), ranging 1.3–50 cm in length, 10–40  $\mu\text{m}$  in cross-section, with uniformity and formability that allows twisting) are suitable for constructing textile fabrics (Moody and Needles, 2004; Mather, Wardman and Rana, 2023). In addition, these fibres require a degree of roughness at their surface, as their conversion into yarns by spinning process depends on their adherence to one another. Success of spinning is further enhanced by the consistency of fibre cross-section (Mather, Wardman and Rana, 2023).

Synthetic fibres (and natural based silk) are made as continuous filament yarns (Figure 2(a)). In some processes continuous yarns are further cut to staple fibres of specified length which yields ‘softer and fuller’ yarn, and which can be employed in knitted clothing, for making carpets or for blending with natural fibres (Mather, Wardman and Rana, 2023).

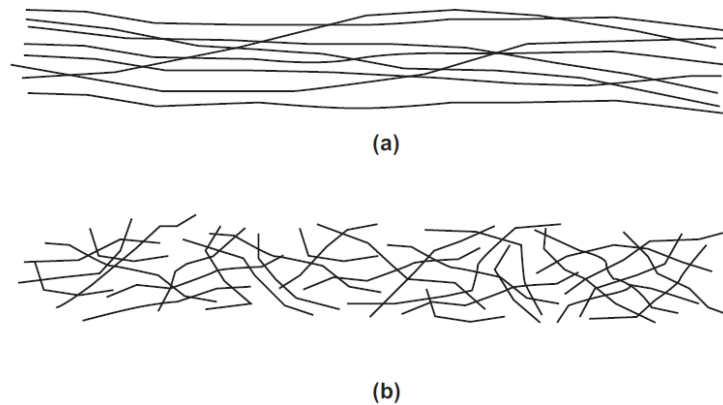


Figure 2. (a) Continuous filament yarn (b) Staple yarn (Mather, Wardman, and Rana, 2023)

Other aspects of the fibre structure and form, the fibre morphology, are also significant. Natural fibres can possess relatively complex morphologies. For example, a cotton fibre

resembles a ribbon with many convolutions with irregular intervals throughout its length (ca. 10 per mm) (Figure 3 (a)) and each fibre is structurally separated into multiple concentric sections with a hollow central core (Textile Academy). Wool fibre surfaces form from overlapping scales (Figure 3 (b)) which create greater friction along surface in direction from fibre tip towards the root than the friction created in opposing direction (also known as directional frictional effect) (Frishman, Smith and Harris, 1948; Mather, Wardman and Rana, 2023).

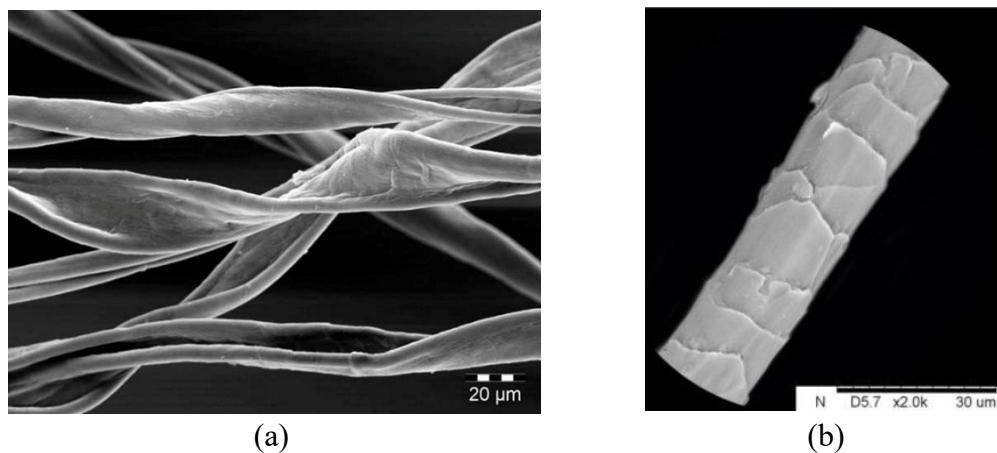


Figure 3. (a) Surface of cotton fibre (modified from Asian Textile Studies. Cotton., 2016) and (b) Surface of wool fibre (modified from Li, Xue and Hua, 2023).

Man-made continuous filament yarns can have a cross-section of various shapes (Figure 4). Considerable proportion of man-made filaments are manufactured to form a circular cross-section (Mather, Wardman and Rana, 2023); others are produced for example with trilobal, pentalobal, crescent shape, hollow or other complex cross sections (Moody and Needles, 2004).

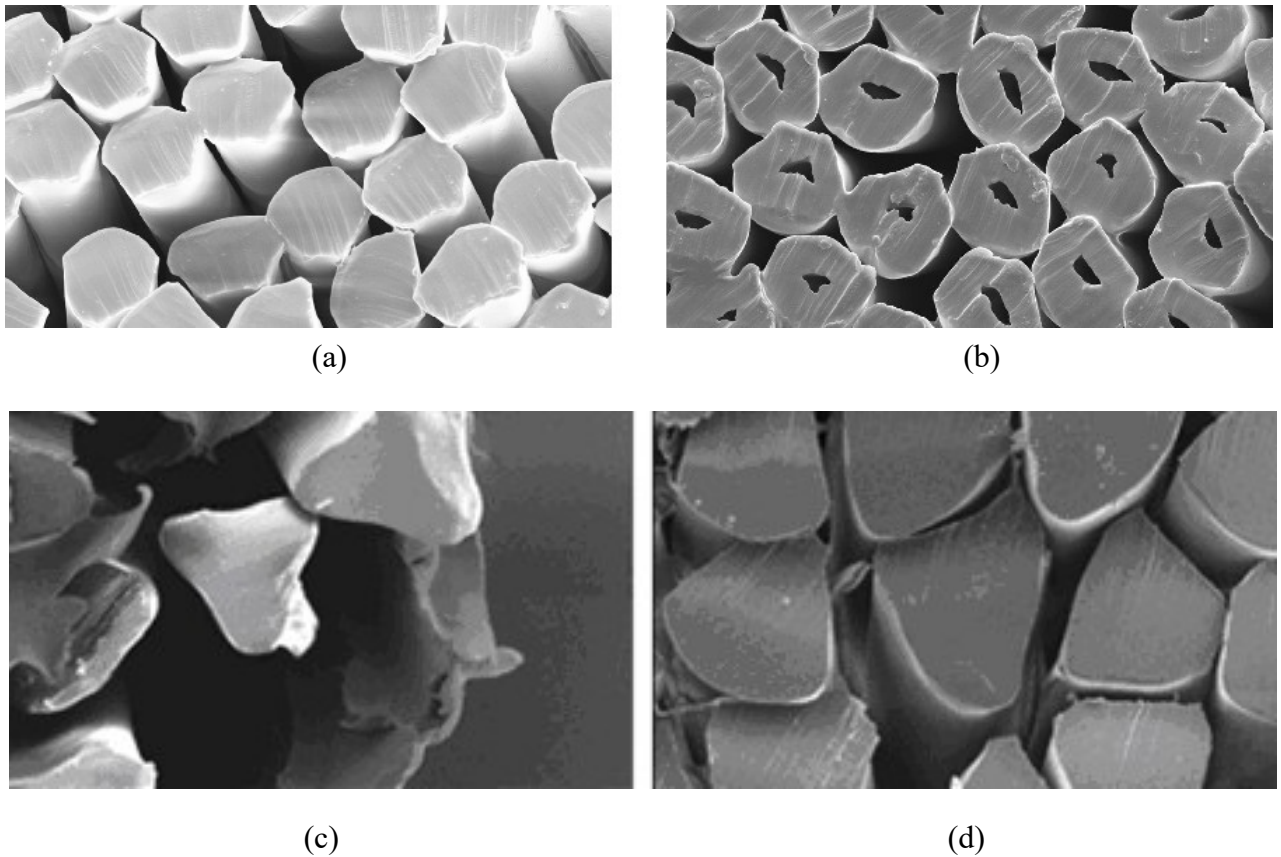


Figure 4. Fiber cross-sections for (a) round and (b) round hollow types (modified from Karaca et al., 2012), (c) trilobal and (d) triangular types (modified from Kara, Erdogan and Erdem, 2012)

The fibre morphology and geometry being important factors, the chemical nature of the polymer forming a textile fibre further determines the numerous properties impacting the functioning of a given fibre as intended in its destined application.

## 2.2 Chemical structure and characteristics

Molecules from around 10 000 and higher relative molecular mass are commonly called as macromolecules. Many of the macromolecules are formed from chains of smaller molecules. If the smaller molecular units are repeated in regular pattern along the chain, the chains are called polymers (derived from Greek word *poly* meaning many and *meros* meaning parts),

and the polymer constructing smaller molecules are known as monomers (Freemantle, 1995).

From the outset and according to Mather, Wardman and Rana (2023), macromolecules, the polymers from which elongated thread-like textile fibres are constructed from, also must be *linear*. In general, polymer chains from bifunctional repeating monomer units only are linear. This linearity allows them to be well packed with high density, resulting in high tensile strength and high melting temperature ( $T_m$ ) (where applicable). More irregularly packed *branched* chains are formed in the presence of trifunctional monomer units, resulting in lower tensile strength and  $T_m$  than with linear polymers. For some polymers bonding occurs between branches and other molecules at specific points of connection forming a *cross-linked* polymer. Elastomers are characteristically composed of lightly cross-linked structures. Polymer with dense cross-linking is referred to having a *network* structure, ie. molecular chains form three-dimensional network and in effect the entire mass becomes one gigantic macromolecule (thermosetting polymers confirm to this structure after curing). These types of polymers tend to be hard and more rigid & brittle. (Metal Metropol 2019; Freemantle, 1995; Mather, Wardman and Rana, 2023)

Flexibility, which is resulting from single bonds allowing rotation in linear polymer chain, reflects the capability of the chain to change its conformation. The potential energy barrier between two conformers determines molecule's ability to change from one to another, which in turn is dictated by the types of bonds in the main polymer chain and by the presence and nature of side-groups. Aromatic rings and other rigid entities in the polymer chain bring about overall chain rigidity. Intermolecular attractions between chains further influence the fibre flexibility. They also impact its strength. Although these attractions are present in any polymer chain constructions due to van der Waals forces, they are further increased by existences of strong dipoles and groups able to form hydrogen bonds, thereby affecting both fibre strength and stiffness (Mather, Wardman and Rana, 2023).

Examples of intermolecular attractions, as outlined by Mather, Wardman and Rana (2023), in natural fibres (possibly representing the strongest intermolecular links amongst fibre-forming polymers) are the keratin chains held together by covalent cross-links in wool (Figure 5). In synthetic fibres an example of intermolecular attractions presence are the extensive hydrogen bonding between  $>C=O$  and  $>N-H$  groups in adjacent chains of polyamide (PA).

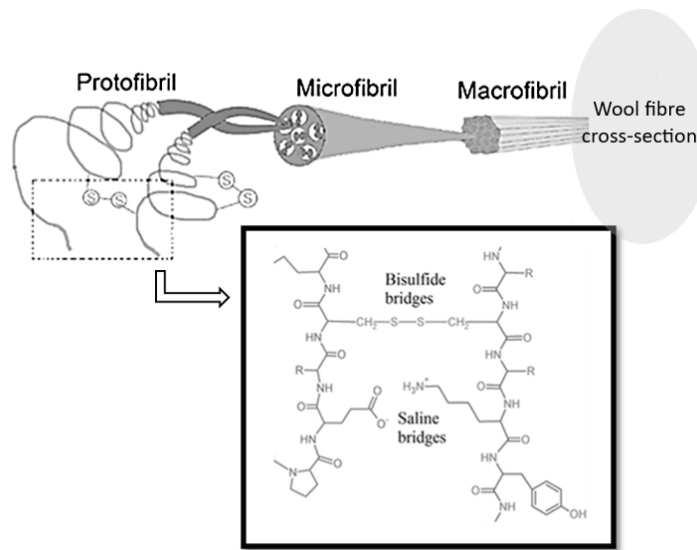


Figure 5. Schematic of wool fibre inner structure illustrating intermolecular links between keratin chains (modified from Fernández-d'Arlas, 2019)

Synthetic fibres polymer chain flexibility and intermolecular attractions also fundamentally influence their  $T_m$ , and their glass transition temperature,  $T_g$ , the temperature at which the polymer becomes softer and transitions to more plastic and rubbery (Mather, Wardman and Rana, 2023).

As well as linearity, *length* is another property of significance for textile fibre comprising molecule. For example, in case of synthetic fibres, too short polymer chain can be problematic to extrude into a fibre or the extruded fibre can be too weak. Should the polymer chain be too long, it will have tendency to become more entangled which can reduce its inherent ability to crystallise, further reducing its strength. In reality, distribution of chain lengths will be present and it can also impact the fibre properties (Mather, Wardman and Rana, 2023). As described by Topham et al. (2023), polymers can be characterised by several different molar mass averages and some of the commonly used methods for characterisation relates to the distribution of lengths. A *number average of molar mass*,  $M_n$ , is determined when the number of polymer chains of each size is counted. A *weight average molar mass*,  $M_w$  is determined if the size of constituent polymer chains is considered. Further, the ratio of  $M_w/M_n$  is called the *molar mass dispersity*. This parameter relates to the breadth of the distribution of molar masses.

Another often-used polymer parameter is the degree of polymerization (DP). This parameter refers to the average number of repeat units in a polymer main chain and it can be used for describing fibres (commonly ranging from DP 500-10 000).

Additional specifications may also be used, for example: polyesters can be characterised by their *intrinsic viscosity* determined in a suitable solvent (Mather, Wardman and Rana 2023).

In textile fibre, the polymer chains would preferably be cohesively oriented in the same direction as the fibre axis and although in numerous natural fibres, and some synthetic fibres e.g. poly(propylene) fibres, the main chain forms helices with central axis aligning in the direction of the fibre axis, in some synthetic high-performance fibres the main chains are almost precisely aligned in the direction of fibre axis (Mather, Wardman and Rana 2023).

## 2.3 Properties and applications of textile fibres

The word ‘textile’ originates from the Latin word ‘textilis’ and the French word ‘texere’, referring ‘to weave’ and originally relating to woven fabrics only. Its meaning has been later extended to encompass fabrics created by alternative methods, for example: cords, braids, embroidery, lace, ropes and threads, and woven, knitted or non-woven fabrics (Patti, Cicala and Acierno, 2021)

Textile fabrics are employed in diversity of applications, e.g. in clothing (to shield, indicate status, follow fashion trends), in homes (e.g. bed linen, rugs, curtains), in transport means (seat belts, airbags, seat upholstery, tires of cars, trains, airplanes) and in construction (as structural reinforcement elements) (Patti, Cicala and Acierno, 2021). This varied range of uses requires a large selection of ‘secondary’ properties (Table 1).

Table 1. Fibre properties (modified from Mather, Wardman and Rana 2023; Sinclair, 2014)

Property	Examples
Mechanical	Tension, Compression, Fatigue failure
Thermal	Glas transition ( $T_g$ ) and melting temperature ( $T_m$ ), Thermal decomposition, Flammability, Thermal Conductivity

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Electrical	Electrostatic charging, Electrical conductivity
Optical	Refraction, Absorption, Reflection, Fibre optics
Surface	Wetting, Adhesion, Friction
Biological	Resistance to microorganisms, Toxicological, Biocompatibility, Controlled degradation <i>in vivo</i> , Biomimicry
Chemical	Alkali/acid resistance, solvent resistance

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As discussed by Moody and Needles (2004) and Mather, Wardman and Rana (2023) the relative importance of these properties is dictated by the end use. E.g. for apparel characteristics such as *softness, flexibility, absorption of moisture and the ability to be dyed* are important; for industrial textiles *strength, greater rigidity and fatigue resistance* are weighted with more significance.

Furthermore, the fibre assembly structure and the end product manufacturing stages can also bear significant importance in the material selection (Mather, Wardman and Rana 2023).

### 2.3.1 Applications

Canavan (2014) broadly divides applications of textile product into categories of apparel, interior, various technical and art (see Table 2).

Apparel, although fundamentally needed for protection, to keep the wearer warm or cool, can also be used to carry various messages in society (e.g. well-being, wealth, status, creativity etc.). Worn textile can also have symbolic meanings, to which colours, decorative patterns or motifs can add more information.

Furnishing and interior textiles although predominantly created for functional purposes (to create comfort as floor coverings, curtains, cushions etc.), in these functions aesthetics also has a role to play and many house-hold art and decorations are also textile based.

According to Canavan, technical textiles are referring to functional products where their aesthetic characteristics are not main priority. These include textiles with industrial applications, smart and medical textiles, wearable technology and some eco textiles. ‘Technology-rich textiles’ are designed with specialist characteristics to satisfy practical and economic solutions.

Industrial and geotextiles include lightweight woven constructs developed for use in structural and civil engineering with beneficial adaptability, strength and non-corrosive properties (e.g. hybrid fabric structures where textiles are utilized in combination with non-textiles including metal or glass for uses such as manufacture of aircraft, or, where woven and nonwoven composite products have been combined with plastics for use in systems designed for drainage systems and reinforcement of soil).

Smart fabrics and intelligent textiles can distinguish changes in surrounding conditions and automatically respond to them, e.g. response to changes in their thermal or chemical environment.

Medical textiles, products used in healthcare sector and personal hygiene products, have become an important aspect of every life in today’s society. Qualities of textile materials used in medical applications have developed and improved and new fabric technologies are now regularly used for example in medical implants. Mono- and multifilament yarns, woven and knitted structures have been engineered for medical and surgical industry with essentially important functions ranging from wound dressings to materials such as artificial ligaments, joints and organs which can be used as implants. Specially designed fibres which can mimic characteristics of human skin (elasticity, temperature) and bandages which are aimed to enhance patient comfort, are all expected to benefit and quicken recovery, and to increase the survival rates in hospitals (Canavan 2014).

Table 2. Textile products applications (broadly categorized) (Canavan 2014)

<b>Application</b>	<b>Sub-category</b>	<b>Examples</b>
Apparel	Casual	Clothes worn to protect and/or as fashion items. Artisan designs to express personal preferences
	Formal/professional	Formal attire (e.g. lawyer), uniform (e.g. military, police, nurse etc.)

---

	Traditional	Special textile worn in ceremonies (e.g. baptism, wedding)
Interior textiles/household products	Interior textile membranes Household practical and decorative items	Upholstery fabrics Bedding and towels, carpets, rugs and curtains
Technical Textile	Industrial and geotextiles	Synthetic woven textiles (with attributes such as lightweight, versatility, strength, non-corrosiveness) used in combination with non-textiles, e.g. metal or glass, as composite materials for manufacture of aircraft and spaceships Engineering membrane materials i. for improving soil conditions for road construction, ii. to prevent coastal erosion
	Smart and intelligent fabrics	Lycra for elasticity e.g. in sportswear; heat and light sensitive textiles
	Medical textiles	Bandages for wounds and burns, artificial ligaments and organs,
	Protective clothing	Heat and fireproof protection, bulletproof clothing
Textile Art	Traditional	Indigenous craftsmen decoration of textile products displaying aspects of a cultural legacy or supernatural and spiritual meaning
	Modern	Decoration of textile products created for aesthetic pleasure, for exhibition, or to one-time commission by textile artisans Exploratory interior textile hangings and tension fabric structures and installations

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This chapter outlined an overview of textile properties and applications, without exhaustively detailed descriptions. The chapter illustrated the variety of practical use of textile fibre-based products in everyday life highlighting the diversity of qualities sought after.

## 3 Polyester fibre

Given the quantity of polyester fibre currently in use and being manufactured for variety of applications, and the forecasted rise of textile fibre demand globally, even if polyester is not considered most environmentally friendly fibre and rather ‘detrimental to the environment’ (United Nations, 2024), efforts to reduce its carbon footprint as much as possible could be seen as a valuable short-term goal in the global efforts towards sustainable textile industry.

### 3.1 History of polyester fibre

In the mid-19th century, the first man-made polymers were created using naturally existing ingredients (e.g. camphor treatment of cellulose, which was obtained from cotton plant, and thereby creating a substance that could be moulded into shapes and used to mimic natural materials such as ivory). In 1907, the first fully synthetic polymer, known as Bakelite, was invented as a result of search for a synthetic substitute for shellac (Science History Institute).

In 1930 the first synthetic fibres were invented by an American chemist, inventor, and the leader of organic chemistry at DuPont, W. Carothers and his research group (Wikipedia, 2025; McIntyre, 2003). First succeeding in synthesising a range of polyesters with molecular weights up to about 4000 by reacting dicarboxylic acids with excess of diols, then (after devising a way to reduce pressure in the reaction container) further to molecular weight of about 12000, the group found that they could draw fibres from the molten product of octadecanedioic acid reacted with an excess of propane-1,3-diol. Further, when these fibres were cooled and subjected to an extensional force, the fibres would extend irreversibly forming ‘oriented fibres of uniformly lower cross-sectional area’, behaviour which the inventors called ‘cold drawing’ (McIntyre, 2003).

As Carothers team synthesised many polyesters (basic patent filed on 1931) this body of work, combined with their research on condensation polymers in general, influenced the scientific community to accept that polymers were (macro)molecules and not assemblies of small molecules in a special state of association (McIntyre, 2003).

Owing to low melting points and issues with low hydrolytic stability, the polyesters synthesised at the time had no commercial value, Carothers team paused the work on polyesters and continued with other polymer classes including PA:s (which had been explored earlier without major success). Arising from these investigations, among others conducted during the same time period, the mid to late 1930s saw the emergence of first commercialised synthetic fibres: the poly(vinyl chloride) fibres (Pe-Ce in Germany, Vinyon in America) and the PA:s nylon 6,6 and Perlon L (nylon 6) (Draper and Mouchiroud (1952); McIntyre 2003).

As chronicled by McIntyre (2003), in 1940 in UK, the British Imperial Chemical Industries (ICI) and Courtaulds started a jointly owned company to produce and retail nylon 6,6 under licence from DuPont. At the same time in UK, J. Whinfield (whose influences were his earlier training in laboratories of C. Cross, the inventor of viscose, and the research carried out by Carothers) initiated a research programme at Caligo Printers Association (CPA) with a goal to realise polyester from ethylene glycol and terephthalic acid. With assistance from newly joined CPA associate J. Dickson, the filing of first patent application took place on 29<sup>th</sup> of July in 1941 (McIntyre 2003).

At the end of 1943 ICI was informed about developments and was advised to negotiate with CPA about possibility to take ownership for further work on the matter. As ICI and DuPont had a research results exchange agreement, ICI also disclosed information to DuPont. DuPont made swift progress (they discovered an improved catalyst) and as ICI acquired worldwide rights from CPA in early 1947 on royalty basis and named their product Terylene, US was excluded due to DuPont having already acquired patent rights from CPA earlier in 1946. The US patent issued to DuPont had number of additions not included in the UK patent. DuPont called their product first Fiber V, then later Dacron. Both Terylene and Dacron brands gained success and by mid-1970s PET fibre production had caught up with volume of PA fibre manufacturing. It has dominated the synthetic fibre manufacturing market ever since (McIntyre 2003; Mather, Wardman and Rana 2023).

Table 3 outlines textile fibre market share of common fibres between 2000 and 2030.

Table 3. Textile fibre market % share (adaptation from Jönsson et al., 2021)

Fibre type	2000	2010	2020	2030
Wool	2.8	1.5	1.1	0.8
Cotton	37.9	32.6	24.9	22.0
Cellulose-based fibres	4.4	4.8	6.2	7.4
Acrylic	5.0	2.5	1.6	1.2
Nylon	7.7	4.9	4.8	4.5
Polyester	36.7	49.0	56.3	58.6
Poly(propylene)	5.5	4.7	5.1	5.4
Elastane	0.3	0.5	0.8	1.0
Total	100.0	100.0	100.0	100.0

Polyester shows the most increase in % share (over 20% in total), far beyond the increase shown by other two fibre types, cellulose-based fibres (3% increase) and elastane (0.7% increase) showing growth in market share.

All other fibres listed, notably cotton with > 15% reduction, show declining % share over the 30-year span.

### 3.2 Chemical structure and manufacturing of polyester fibres

If classified as per ester chemistry, *polyester fibre* can refer to fibres manufactured from poly(ethylene terephthalate) (PET) and also from poly(trimethylene terephthalate) (PTT), poly(buthylene terephthalate) (PBT), poly(ethylene furanoate) (PEF), poly(ethylene naphthalate) (PEN) and from other polymers allowing fibre formation, such as: poly(carbonate) (PC), poly(lactic acid) (PLA), poly(ethylene oxalate) (PEO), poly(buthylene succinate) (PBS), poly(hydroxyalkanoate) (PHA) and others (Aizenshtein 2006; Mather, Wardman and Rana 2023, Textile Exchange 2024, a).

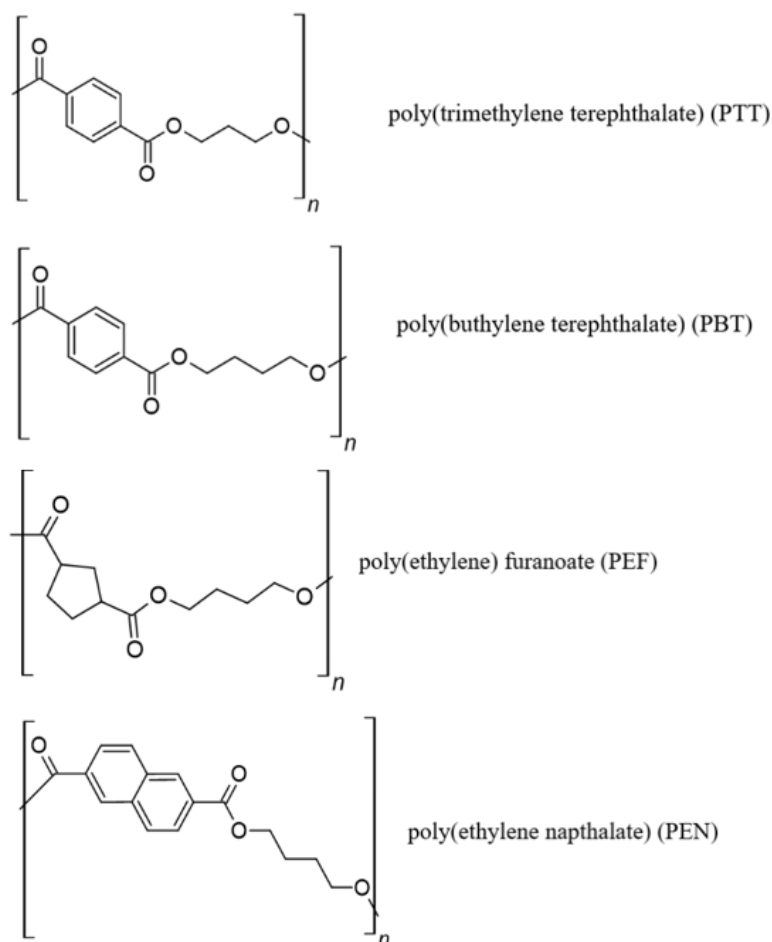


Figure 6. Examples of polyester structures

However, according to European Union regulation No 1007/2011 on *textile fibre names and related labelling and marking of the fibre composition of textile products*, textile fibre can be called polyester should the fibre be formed of linear macromolecules comprising at least 85% (by mass) in the chain of an ester of a diol and terephthalic acid (European Union, 2011).

According to (US) 16 CFR Part 303 § 303.7, *generic names and definitions for manufactured fibres*, polyester is a manufactured fibre in which the fibre-forming substance is any long chain synthetic polymer composed of at least 85% by weight of an ester of a substituted aromatic carboxylic acid, including but not restricted to substituted terephthalate units, and para substituted hydroxy-benzoate units.

Currently polyester fibre market is dominated by PET and as of today, the other polyester fibre types have had lesser commercial presence so far (Mather, Wardman and Rana 2023). The next part of this chapter describes structure and manufacture of PET fibre only. Alternatives to PET fibre are briefly visited under 3.5.2 Bio-based section.

### 3.2.1 PET structure

Chemical structure of PET polyester can be seen in Figure 6. As with all polyesters, the monomeric units of PET, ethylene glycol (EG, IUPAC name: ethane-1,2-diol, EC/List no.: 203-473-3, CAS no.: 107-21-1) and terephthalic acid (TA, IUPAC name: benzene-1,4-dicarboxylic acid, EC/List no.: 202-830-0, CAS no.: 100-21-0) (<https://chem.echa.europa.eu/>) (shown in Figure 7), are joined together by ester linkage, -CO-O-.

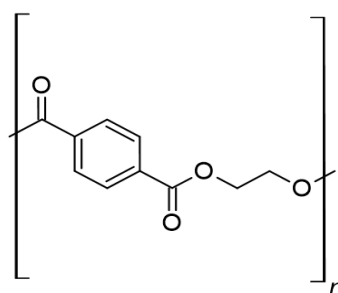


Figure 7. Chemical structure of poly(ethylene terephthalate)

PET manufacturing begins with the manufacturing of the constituent monomers consumed in the polymerisation reaction.

### 3.2.2 PET synthesis - overview

In the past PET manufacturing was carried out by method referred to as ‘dimethyl terephthalate (DMT) method’ with DMT and EG, in presence of catalyst, as the starting monomers. At the time, the use of TA as the comonomer for PET synthesis was prevented due to presence of impurities. At present, although DMT remains as raw material for the synthesis of PBT, the DMT method for PET synthesis has been by and large replaced by use

of TA and EG as the starting materials, the so called ‘terephthalic acid (TA) method’, which became industrially feasible after improvements (1955 invention of bromide-controlled air oxidation by two actors, the Mid-Century Corporation and ICI, both having applied for patent on same date) in commercial TA manufacture, during which p-xylene solution of ethanoic acid is oxidized using oxygen in presence of cobolt-manganese-bromine catalyst (Deopura and Padaki 2014; Mather, Wardman and Rana 2023).

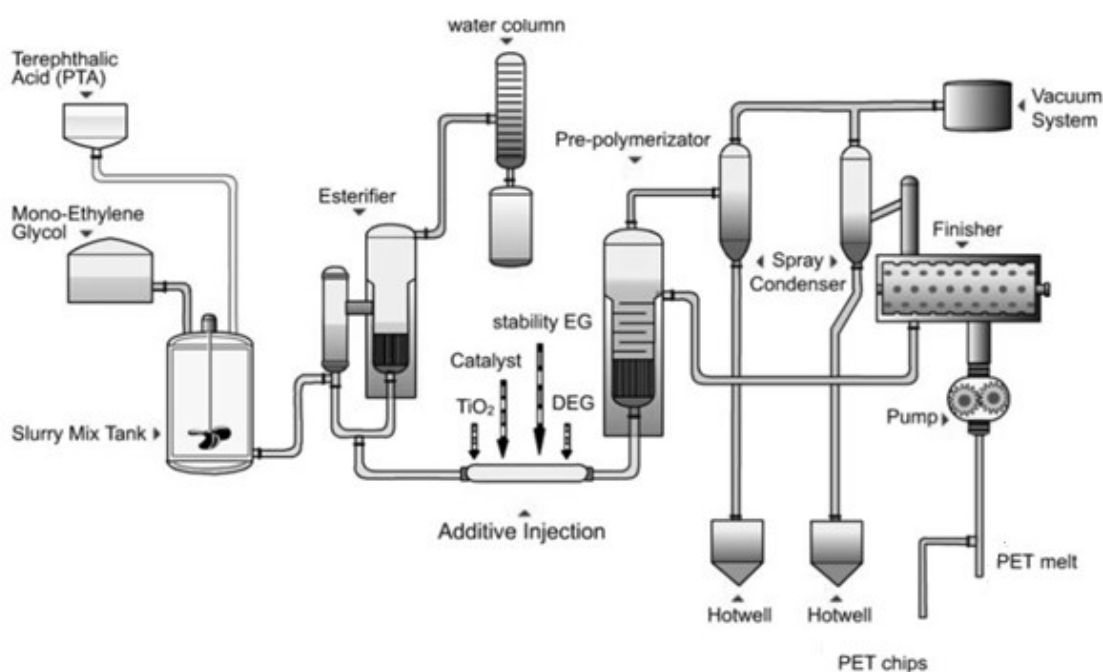


Figure 8. Schematic of PET manufacturing (modified from Puli, Sabavath and Paul, 2021).

Main steps of PET manufacturing as outlined in Figure 8 are: i. Continuous feed of raw materials directed into a paste preparation vessel in which no chemical reaction takes place yet; ii. Esterification/transesterification carried out in two reacting chambers: the paste being first transferred into esterification reactor number one, in which the reaction proceeds to above 90% conversion, followed by second reacting chamber in which the reaction proceeds to more than 96% conversion; iii. Pre-polycondensation/pre-polymerisation step during which the esterification degree increases to more than 99% and the chain length of the polymer increases; iv. Growth polymerisation/polycondensation step during which pre-polycondensation product is fed to the finishing reactor which is subjected to vacuum and elevated temperature. After this molten PET is further processed to various forms such as fibres or granules (Puli, Sabavath and Paul 2021).

In the direct PET esterification from purified TA and EG, the two comonomers are required in 1:1 equimolar ratio. To control this stoichiometry, the first reaction to be carried out is to produce bis (hydroxyethyl) terephthalate (BHET) (see Figure 9(a)) after which polycondensation follows (see Figure 9(b)). This method offers number advantages in comparison to the DMT method (Mather, Wardman and Rana 2023): i. if required, the TA method allows formation of PET grades with higher molar mass and ii. the direct esterification reaction is catalysed by the -COOH groups present (albeit stronger acids can be introduced as additional catalysts) (Mather, Wardman and Rana 2023).

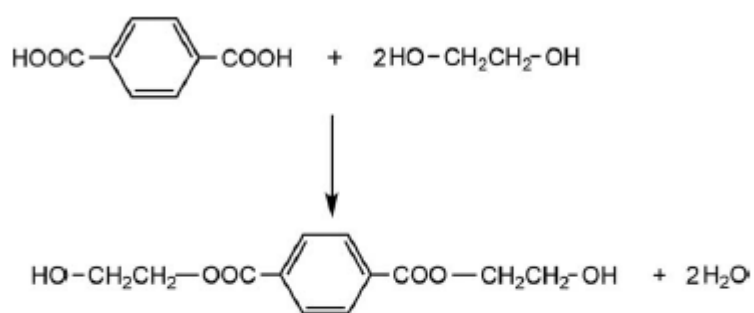


Figure 9(a). 1st reaction in PET polymer synthesis (TA method), condensation, yielding bis (hydroxyethyl) terephthalate and water (Mather, Wardman and Rana 2023)

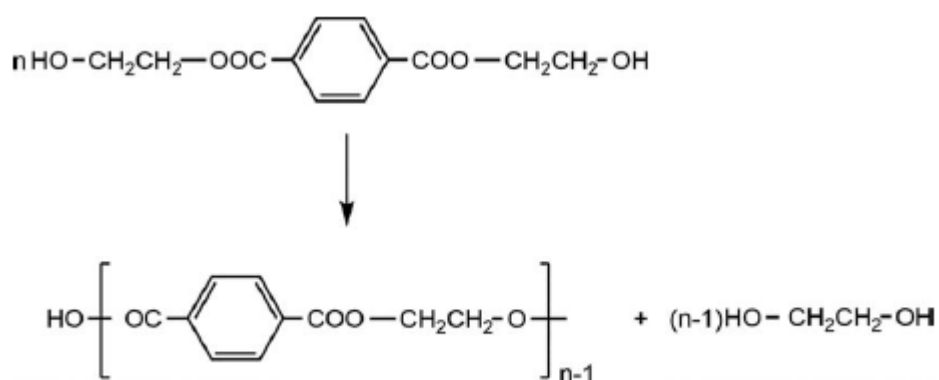


Figure 9(b). 2nd reaction in PET polymer synthesis (TA method), Step growth polymerisation (polycondensation) of bis(hydroxyethyl) terephthalate (Mather, Wardman and Rana 2023)

As the step growth polymerisation (polycondensation) of bis(hydroxyethyl) terephthalate is a reversible reaction, it is necessary to remove the EG produced during polymerisation reaction to allow the process to progress forward. EG is removed under vacuum and can be recycled as a starting material for the esterification process (Mather, Wardman and Rana, 2023).

### 3.2.3 PET fibre manufacturing

In general, production of synthetic fibres from polymer granules requires several consecutive manufacturing processes; First the granules must be converted to a liquid form, mostly either as a melt, which, according to Moody and Needles (2004), is the least complex of fibre spinning methods, or as a solution.

In the case of PET, and other polyesters, if not already in melt form directly from the polymerisation process, the polymer chips are converted to a melt by feeding them into a screw extruder, which contains a series of heated chambers. Molten polymer is transported to spinning blocks, via fine filter, under high, 100-200 bar pressure through (gear) metering pump, which provides a continuous, steady flow of polymer through spinneret holes. Filtering prior to spinneret removes any unwanted solid impurities and gas bubbles (Mather, Wardman and Rana, 2023; Puli, Sabavath and Paul 2021).

Molten polymer is extruded (spun) under constant high pressure through the tiny holes of a spinneret to form continuous filaments. Melt temperature control, and thereby the control of melt polymer viscosity, is required for successful filaments formation.

Upon exiting the spinneret, molten filaments are quenched by a laminar and uniformly controlled and conditioned airflow which solidifies the filaments. Quench air enhances uniform solidification of filament/fibre. These cooling conditions may also have direct influence on the resulting polyester fibre properties. Other processing variables include i. the spinneret hole diameter (preferably over 3 times the size of polymer particle diameter) and ii. the tensile stress applied on the melt stream (which should not exceed filament tensile strength), i.e. take up velocity of the filament has to be carefully controlled and aligned with the spinning speed (Mather, Wardman and Rana, 2023; Puli, Sabavath and Paul 2021).

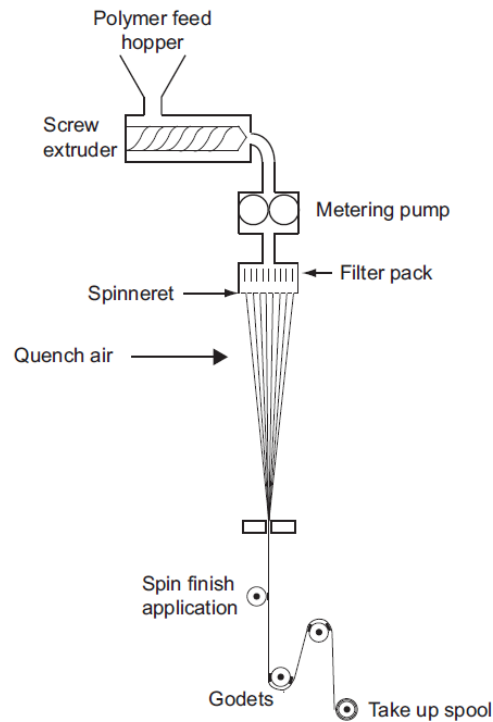


Figure 10. Schematic of melt spinning process (Mather, Wardman and Rana 2023)

After extrusion, as the filaments cool and solidify, they are subjected to controlled tensile force/elongation. This controlled stretching of fibre filaments in both molten and solidified states, also called drawing, will enhance the polymer molecular structure orientation allowing chains to align along the fibre axis to yield sufficient strengthening for intended applications. The spun filaments are gathered to form a multifilament yarn and for some applications, in particular for apparel, the yarn is also often texturized using one of the various methods (such as gear crimping, false twist, knife edge, knit-de-knit) to acquire desirable aesthetic properties, to improve comfort and to improve thermal insulation. As the yarns may possess a significant degree of heat shrinkage (magnitude depending on the degree of crystallinity and overall orientation of the polymer chains), the thermoplastic fibres can also be permanently heat set after drawing and orientation. This heat treatment causes the intermolecular bonds linking adjacent polymer chains to weaken increasing their mobility. The relaxation process then further leads to re-formation of intermolecular bonds inducing further crystallisation and stabilisation of the fibre structure (Moody and Needles, 2004; Mather, Wardman and Rana, 2023).

Yarns/texturized yarns can be further cut into staple fibres.

### 3.3 Properties and uses of polyester fibre

Polyester fibres all have similar properties. They are resilient, they are resistant to wrinkling, they have high durability and dimensional stability, and they are relatively resistant to chemical and environmental attack. Owing to the good balance of cost and performance (Aoyama and Tanaka, 2016) PET fibres are used in variety of applications: apparel, household, medical and industrial (including geotextiles). In apparel, PET fibres are often used in blends with other fibres (for example polyester/cotton and polyester/wool fibre blends are used apparel and household textiles). Medical applications of PET include sutures, heart valves, artificial tendons and ligaments, orthopaedic bandages, and surgical hosiery. Industrial applications include vehicle tyre reinforcement, ropes, tents and sail canvases. Special PET fabrics are also used for reinforcement and drainage to stabilise soil in road construction (Moody and Needles, 2004; Mather, Wardman and Rana, 2023).

Table 4. PET fibre properties with fibre properties of cotton and wool (Mather, Wardman and Rana 2023)

Property	PET	COTTON	WOOL
Specific gravity	1.38	1.54	1.32
Tenacity, cN tex <sup>-1</sup>	35-56, upto 100 for high tenacity yarns	25-40, upto 20% stronger when wet	9-15, reduced to 7-14 when wet
Elongation at break, %	15-40; 5-10 for high tenacity yarns	5-10	25-35 ambient conditions, 25-50 wet
Elastic recovery, %	80 from 8% stretch	45 from 5% stretch	> 50 from 10% stretch
Melt temperature, °C	ca. 260 °C	NA	NA
Resilience	High	Low	Very high
Abrasion resistance	High	Good	Apparel: low, carpet: high
Moisture regain, %	0.4	8.5	14-18
Launderability	Garments can withstand vigorous wash treatments.	Garments can withstand various wash and dry treatments; they dry slowly and crease easily.	Garments require washing with care, normally below 50°C. Agitation (during wash

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or dry) can induce felting.

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Table 4 outlines general properties of PET fibre in comparison with cotton and wool fibres. PET fibre has the highest tenacity and the lowest moisture regain.

### 3.4 Environmental considerations

There are concerns about the impact of polyester fibre on the environment. The negative impact associated with fibre and textile production and processing e.g. manufacturing/upstream waste created, considerations during and after use e.g. microfiber shedding during fibre lifetime (Figure 11) and quantity of textile fibre ending in landfill, including the amount of time it takes to degrade, are all of importance.

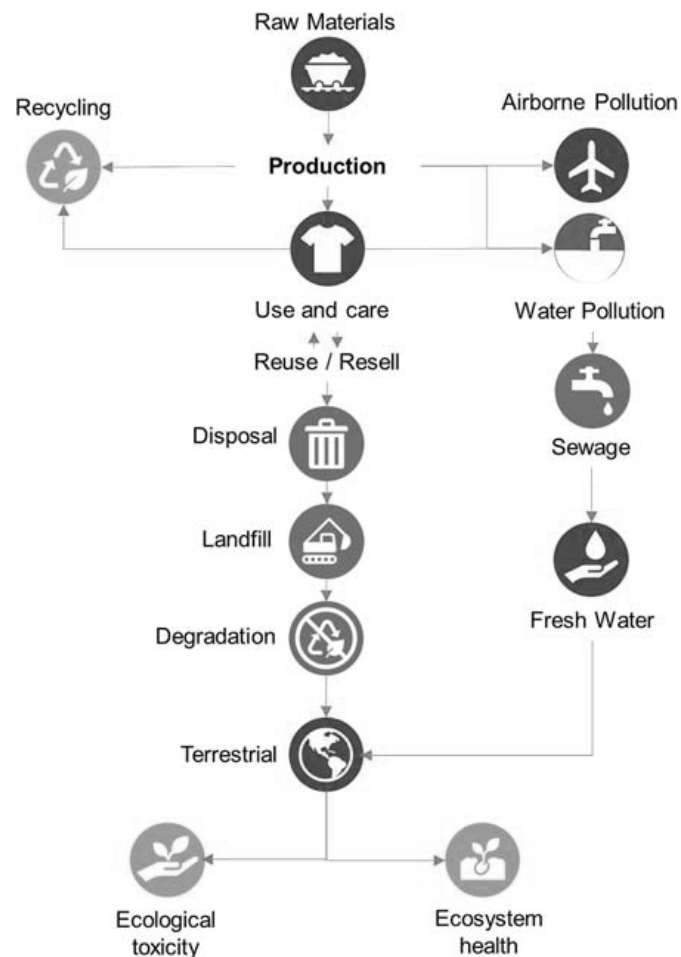


Figure 11. Points of textiles microfibre release during the product's life cycle (adapted from Kikutani, Schriever and Lee, 2024).

Although it can be assumed a reduction of polyester fibre manufacturing will automatically reduce all hazards from polyester fibre related source, considerations that should possibly be carefully weighed out include:

- i. the durability of polyester fibre (Moody and Needles 2004) which can enhance some aspects of recycling and re-usability
- ii. the carbon footprint of polyester fibre in comparison to current alternatives. As outlined by Hasslinger et al. (2019), although cotton is classified as a renewable source of textile fibres, its ecological footprint is similar and at times even larger than the ecological footprint of polyester (Haslinger et al., 2019). Also, PA fibre, the second most common type of synthetic fibre manufactured globally, equates to considerably higher carbon footprint per volume produced than polyester fibre (Textile Exchange, 2024 b)
- iii. review of all sources of microfibre and the possible ways on how to reduce the overall quantity reaching environment. Although in general, microfibres are thought to originate to be from synthetic sources (e.g. PES or PA textiles), fibres from natural origin, e.g. wool and cotton have also been found from ocean (Le Guena et al., 2020) and laundry effluent (Cesa et al., 2020; De Falco et al., 2020; Hazlehurst et al., 2023). Study comparing *PES only knit/filament*, *PES only knit/stable* and *PES:cotton 50:50 knit/stable* blends-based apparels reported greater release of fibres, to both laundry effluent water and air, from the PES:cotton blend article. To effluent water, the release of microfibres from PES-cotton blend was over twice the quantity of other two compositions studied and the fibre released to both water and air originating from this blend was over 75% of cotton (De Falco et al., 2020).

Regardless of nature of the microfibre, they all potentially function as carriers for pollutant chemicals. Although the effects of any type of microfibres on the global environment are currently not fully understood (De Falco et al., 2020), studies carried out on microfibre impacts on freshwater and terrestrial ecosystems have

demonstrated various species having being impacted by their presence (Kwak et al., 2022)

### 3.5 Future of polyester fibre

According to Kikutani, Schriever and Lee (2024), in this present time, man-made and synthetic fibres could be seen to offer openings for innovation and shift towards more eco-friendliness. In the case of PES fibres, recycling strategies will present an ever-increasing importance. Monomaterial textile sources, renewable raw materials and enhanced degradation of PES fibres are all part of the solutions for challenges associated with PES fabrics recycling, increasing manufacturing sustainability and combatting fugitive microplastics (Kikutani, Schriever and Lee, 2024).

#### 3.5.1 Recycling

In general, there is justification for argument that in comparison to textile incineration or landfilling, textile recycling is a preferable way of dealing with textile waste (Sandin and Peters 2018), yet important considerations in relation to textile recycling exist. For example: (i) in case of low replacement rates, the impact of the entire recycling processes, which includes sorting and transport of material, may be larger than the benefits of prevented production, causing net increase of the impact; (ii) depending on recycling approach and the type of prevented production, problem shifting may occur, ie. one particular negative environmental impact may increase although other will decrease (e.g. negative environmental impact can increase if the recycling process consumes lot of fossil-based energy and the replaced material is made by a relatively climate-friendly fibre such as cotton) (Roos et al., 2019).

To reduce negative impact on environment and to promote most ecologically sustainable textile production and processing, reduction in consumption and selective manufacture, followed by the aim for the most environmentally friendly textile manufacturing materials and processes, producing products with optimized user life span and options for direct re-use/recycling whenever possible, should be prioritized in decision making. After this, when

considering recycling of the textile material only (not the entire article as it is), recycling of fabric may be more energy conserving/preferable option to recycling at fibre level. When recycling at fibre level is selected as the best way forward, decision between mechanical and chemical recycling of the given type of textile fibre is to be considered. Mechanical recycling of fibres (which includes recycling at fibre and polymer level) can be the appropriate choice for many applications. Chemical recycling of textile fibres (which includes recycling at oligomer and monomer level) can yield better quality product than mechanically recycled (aim of the recycling process being recycling or upcycling of the fibre). I.e. where the quality of mechanically recycled textile fibre may deteriorate by each cycle and depending on the overall recycling process the material may only be able to go through limited number of recycling cycles (and for these reasons has limited applications in comparison to the virgin fibre) the chemically recycled textile fibres can have quality comparable (or even higher) to similar virgin fibres on the market (Haslinger et al., 2019; Seifali et al., 2025).

Mechanical recycling of PET, representing over 10% of global PES fibre production in 2023, is already established in textile manufacturing industry. It is noteworthy that currently the raw material for mechanical recycling consists primarily of plastic bottles made from PET. Other sources, such as ocean waste, packaging waste and pre-consumer processing residues (e.g. fabric scraps), are also used (Textile Exchange, 2024 a).

Resourcing post-consumer PET bottles and other packaging materials for fibre manufacturing is expected to get increasingly harder due to food packaging industries themselves transferring to employ recycled materials in their own processes (not least due to sustainability requirements potentially imposed on themselves by EU legislation in Europe) (Textile Exchange, 2024 b). In contrast to PET bottles, mechanical recycling of PET fibres and textiles is often not as straight forward, primarily caused by challenges presented in collecting and sorting high purity PET textile for raw material. Production of monomaterial fabrics/garments are seen as one solution to this issue (Kikutani, Schriever and Lee, 2024).

Although currently recycling rates of PET products other than PET bottles are low in general and PET based textiles have not reached circularity yet (Systemiq, 2023), in recent years, interest in chemical recycling has increased in textile industry according to Textile Exchange (2024 b). Multiple startups and more established recyclers are currently working to develop

technologies which are capable of handling the quantities and varieties of PES currently in use, including various blends (Textile Exchange, 2024 b).

In 2023 report released by Systemiq and based on their quantitative system model and scenario assessment carried out (where material flows and environmental implications of future scenarios were assessed for a ‘high-circularity, low-emissions European PET system’), circular economy solutions for all PET based products (in particular consumer packaging and textiles), involving ‘upstream’ approaches of:

- i. extended product lifetimes,
- ii. reversed trends of high-consumption business,
- iii. standardised product design to enhance reuse and recycling profitability (in case of textiles this would require shift to less complex end products),

and ‘down-stream’ approaches of:

- i. secured long-term demand for recycled PET polyester (recommendations/requirements of recycled content across all end-use applications, including textiles)
- ii. improved feedstock flows for recyclers by optimised waste collection/sorting (would require effective return schemes for textiles after-use)
- iii. scaled up recycling infrastructure (would require development of complementary mechanical and chemical recycling flows where mechanical recycling volumes of all PET would increase by two-thirds from 2020 and chemical recycling - with recycled PET (rPET) production volume set to over half the quantity of mechanically produced rPET volume - would be aimed for re-charging the system with virgin-like PET without fossil-based raw materials)

could see (PET-based products) landfill and incineration to be reduced by 70% and greenhouse gases emissions could be halved by 2040. This is according to Systemiq ‘ambitious complementary scenario’ in which PET textiles recycling rates would increase to ~ 45%. Additionally, according to Systemiq (2023), although the earlier listed approaches are already currently supported by the existing regulatory framework for PET packaging, *the regulations supporting actions regarding PES textiles remain under development and the*

*textile system requires urgent transformation to i. reduce demand increase through circular business models and ii. significantly accelerate recycling rates (Systemiq, 2023).*

### 3.5.1.1 Chemical Recycling of PET

Chemical recycling methods for PET textiles include hydrolysis, methanolysis, glycolysis and (biochemical) enzymolysis. Depending on approach selected, polyester can be partially or fully depolymerized into monomers or oligomers (such as TA, DMT and others, Table 5) which are further processed and chemically converted back into PET textile fibre using conventional manufacturing techniques (Textile Exchange, 2024 b).

Table 5. Commonly studied chemical recycling methodologies of PET compared with mechanical recycling (adapted from Nandi et al., 2023).

Method	Process output	Process dependency on raw material quality	Quality of yielding rPET	Cost/Energy consumption
Hydrolysis	TA and EG	No	Comparable with Virgin PET	Highly cost intensive
Methanolysis	DMT and EG	No	Comparable with Virgin PET	Cost intensive
Glycolysis	BHET	No	Comparable with Virgin PET	Cost intensive
Enzymatic depolymerization	Mono(2-hydroxyethyl) terephthalate (MHET) or BHET	Yes	Comparable with Virgin PET	Highly cost intensive
Mechanical recycling	rPET	Yes	Lower than Virgin PET	Cost effective

According to Nandi et al. (2023), global warming potential of virgin PET is estimated four times higher than of recycled PET and the potential environmental benefits recycled PET

offers is not reflected in the current cost of recycling. In the review conducted, glycolysis was identified as the potentially most cost-effective method for chemical recycling (Nandi et al., 2023).

### 3.5.2 Bio-based

‘Bio-based materials’ are materials comprised of naturally occurring organic compounds of biological origin or are materials *fully* or *partially* derived from biologically renewable natural resources (Egan and Salmon, 2022, García-Vel’asquez and van der Meer, 2022).

According to Aoyama and Tanaka (2016) *bio-based PET* can be manufactured by using *bio-based EG* and *bio-based TA* as raw materials in already existing manufacturing facilities. No economically significant naturally available sources of pure EG are known to exist (Australian Government. Department of Climate Change, Energy, the Environment and Water, 2022) and TA, although classified as a natural, organic substance (SIDS, 2001), is mainly categorised as an industrial chemical intermediate (SIDS 2001) with major commercial routes for appropriately high quantities for industrial processes currently originating from fossil-based petroleum and not from any directly harvestable renewable natural source (Kohlstedt et al. 2022). Therefore, to enable bio-based PET manufacturing, manufacturing of bio-based EG and bio-based TA are required first.

Studies of different approaches have been conducted (Table 5) to find synthesis pathways for bio-based EG and TA and some commercial processes are already established: bio-based EG has been manufactured by India Glycols Ltd since 1989 (Aoyama and Tanaka, 2016) and Coca-Cola introduced bio-based PET bottles (produced with approx. 30% wt bio-based EG as raw material) in 2009 (García-Vel’asquez and van der Meer, 2022).

Trial manufacturing of 100% bio-based PET film and fibre was successfully completed by Toray together with Gevo in 2011. In this joint-trial, Gevo manufactured bio-based paraxylene by first producing isobutylene through dehydration from isobutanol, which in turn was a fermentation product of sugar originating from biomass. Toray (using its own proprietary technique) converted the bio-para-xylene into TA, followed by conversion into bio-based PET fibre and film. Other companies (Virent, Anellotech) have also looked into industrialization of bio-based paraxylene (Aoyama and Tanaka, 2016).

Table 6. Examples of bio-based EG and TA manufacturing routes from literature

Bio-based Product	Raw Material	Methodology/Process	Reference
EG	Bio-based ethanol from first- (food crops e.g. sugar beet) and second-generation feedstocks (e.g. <i>miscanthus</i> )	Dehydration of ethanol to ethylene intermediate used in OMEGA process	García-Vel'asquez and van der Meer 2022
TA	Bio-based para-xylene (precursor to) TA from wood chips feedstock	Biocatalytic process	Coons 2021
TA	Lignin	Hydrothermal depolymerization of lignin, fermentative conversion, chemical conversions	Kohlstedt et al. 2022
TA	Bio-based naphtha produced from waste & residue oils, (incl. used cooking oil)	Naphtha conversion to bio-para-xylene and further into high-purity TA	Coons 2023

As discussed by Aoyama and Tanaka (2016), in the future, both bio-based EG and bio-based TA acid could be expected to stabilize their markets after their currently relatively high costs in comparison to fossil-based products are mitigated (Aoyama and Tanaka, 2016). In an environmental assessment on bio-based PET carried out by García-Vel'asquez and van der Meer (2022) the authors point out that for example in Europe, a regionally produced supply of EG could provide both economical and environmental benefits in comparison with current material streams which rely on imported products from world's other regions (García-Vel'asquez and van der Meer, 2022). It would be important to continue assess supply stability based on so called second (and third) generation, non-edible feedstocks (Aoyama and Tanaka 2016) and the potential impacts from increased biomass production (e.g. depletion of resources (land, water), potentially increased use of fertilizers and pesticides) needs to be assessed (Jönsson et al., 2021; García-Vel'asquez and van der Meer, 2022).

Structurally closely related bio-based alternatives to bio-based PET, which also fit the European Union regulation No 1007/2011 on marking of the fibre composition of textile product as a 'polyester', also exist.

Poly(trimethylene terephthalate) (PTT) can be manufactured using bio-based propanediol (obtained via fermentation of sugars, process successfully commercialized by DuPont (Aoyama and Tanaka (2016))). PTT fibres exhibit significantly high resilience due to its elastic nature. PTT fibres are used as carpet face yarns and in stretch apparel (incl. sportswear) and in upholstery (Mather, Wardman and Rana, 2023).

DeRosa et al. (2020) reported synthesis of bio-PBT (butylene terephthalate) from bio-based butylene glycol (BG) produced from sugar (DeRosa et al 2020). Currently production quantity of PBT remains small due cost. It's benefits as a fibre include it being easily dyed and being suited to stretching materials (Mather, Wardman and Rana, 2023).

Renewable, bio-based PES alternatives to PET include PEF manufactured with bio-based feedstock of furandicarboxylic acid (FDCA) as raw material (Eerhart, Faaij and Patel, 2012; Anonymous, 2023; Mather, Wardman and Rana, 2023) and poly(lactid acid) (PLA) (Jönsson et al 2021; Mather, Wardman and Rana, 2023).

In some contrast to other industrial sectors (e.g. flooring, automotive), pertaining to textile fibres manufacturing, the uptake of bio-based alternative materials to PET on the market has been low due to number of reasons: i. cost, ii. properties of fibre and fabric (e. g. reduced abrasion resistance and lower melting point of PLA) and iii. the challenges in availing of support from the auxiliary business to develop new dyeing and finishing chemicals for novelty fibres (Jönsson et al., 2021).

### 3.5.3 Carbon capture

According to Howard (2023), carbon capture and storage (CCS) or carbon capture, utilization and storage (CCUS) are concepts referring to technologies which can reduce carbon dioxide (CO<sub>2</sub>) emissions from fossil fuel burning, by capturing the CO<sub>2</sub> before it gets released into the atmosphere. In 2023, CCS projects were storing close to 45 million tons of CO<sub>2</sub> annually, this equals approximately the amount of CO<sub>2</sub> emissions created by 10 million passenger cars. By enlarge, capture takes place at stationary sources of significant amounts

of CO<sub>2</sub>, e.g. power plants or industrial cement and steel manufacturing plants and although options to remove CO<sub>2</sub> directly from air are also been considered, these methods are currently less efficient in the capturing due to the concentration of CO<sub>2</sub> being about 300 times less in the air than in industrial plant flue gas emissions. Today's carbon capture systems mostly employ liquid to chemically extract the CO<sub>2</sub> from flue gasses, yet several novel capture processes are under development. The captured CO<sub>2</sub> gas is compressed to a liquid-like form and transported to a storage site (most commonly through a pipeline. More expensive ship transport is being considered in Europe and Japan). Once at storage site, CO<sub>2</sub> is pumped down to ground below 750 m into geologically 'available' locations e.g. used-up oil and gas reservoirs (Howard, 2023; Textile Exchange, 2024, b).

At the moment, the main utilization of CO<sub>2</sub> is enhanced oil recovery (EOR). In EOR CO<sub>2</sub> is injected into active oil reservoirs to allow recover more, otherwise difficult to extract, oil. CO<sub>2</sub> is used in manufacturing of chemicals and fuels (for the captured CO<sub>2</sub> the opportunity being its potential to offer an identical monomer to fossil-fuel based production of synthetics, while avoiding input of any new virgin fossil-fuels), yet these processes involve large quantities of carbon-free energy, which currently elevates the costs above competition (Howard, 2023; Textile Exchange, 2024, b). Additionally, pure CO<sub>2</sub> fertilizer can be used in greenhouses growing plants (studies have demonstrated improvements in crop yields) and although currently most CO<sub>2</sub> used for enrichment in agricultural greenhouses is extracted from the earth, captured CO<sub>2</sub> can be used in similar manor. CO<sub>2</sub> can also be used to grow algae and bacteria which can be further converted to biofuels, fertilizers or animal feed (Ghiat,I et al. 2021; Howard, 2023).

For larger scale implementation of CCUS, use of CO<sub>2</sub> is estimated to consume around 10% of the captured CO<sub>2</sub> (Ghiat,I et al. 2021; Howard 2023). Globally the total amount of CO<sub>2</sub> emitted into atmosphere is so high that if capturing it is aimed to be significant part of climate change mitigation, most of the captured CO<sub>2</sub> will need to be stored underground. However, use of captured CO<sub>2</sub> could help in reducing the associated cost and allow more companies to invest in capturing their emissions (Howard, 2023).

CO<sub>2</sub> could also be used as a feedstock instead of fossil fuels in manufacturing of many products. Research has been carried out on transferring CO<sub>2</sub> into plastics, building materials e.g. cement, carbon fibres, household products such as baking soda, bleach, inks and also as a base for textile fibres. Some of these products are already sold in the market in low volumes

and alongside recycled and biobased feedstocks, CCUS can help in transfer from fossil-fuel based production to alternative feedstocks (Howard, 2023; Textile Exchange, 2024, b).

As outlined in Textile Exchange (2024, b) report, more research is needed to verify the ability of the new technologies to produce synthetic materials which can reduce greenhouse gas emissions and would allow scalability too. In relation to textile industry, although there is special interest in using CO<sub>2</sub> as a feedstock in synthetic fibre manufacturing, it should be noted that CO<sub>2</sub> can potentially be used as a feedstock across other fibres and materials (e.g. cotton, viscose and lyocell) too (Textile Exchange, 2024, b).

Examples of carbon capture technology being already used in PET manufacture include CleanCloud® PES manufactured using CarbonSmart™ technology by LanzaTech. In this solution, captured CO<sub>2</sub> emissions are converted into EG allowing 30% replacement of virgin PET whilst rest of the feedstock is virgin TA. The production of the CleanCloud® PES is a multi-step process, which involves multiple actors. Utilizing a commercial-scale process, LanzaTech captures CO<sub>2</sub> emissions from industrial processes and CarbonSmart™ ethanol is produced via fermentation. Company then works with India Glycols Ltd to convert ethanol into EG, which is then further supplied to Far Eastern New Century, to process it into PET. The development of the process was simplified due to CarbonSmart™ EG having equal properties to EG based on fossil raw materials, enabling it to be a ready re-placement in an existing process (Textile Exchange, 2024, b).

100% carbon capture PES textile fabric was included in Super Textile Corporation ([www.supertextile.com](http://www.supertextile.com)) product offerings in late 2024 (correspondence 09.06.2024).

#### 3.5.4 Biodegradability

‘Biodegradable’ refers to material’s response to specified external conditions (Egan and Salmon, 2022).

Total approximated quantity of 3.5 billion tonnes (Bt) of textile fibres (approx. half of which generated during the last 20 years) have been manufactured since the beginning of 20<sup>th</sup> century. From this overall quantity, estimated under 0.4 Bt of waste textile has been recycled (mostly downcycled). Should current textile manufacturing pace persist with no significant

change in adaptation of recycling technologies, total quantity of 6.1 Bt of textile fibres will have been generated by year 2040, leading to an overall textile waste volume of over 4.5 Bt (Jönsson et al., 2021). Currently the textile waste represents approximately 3% of the total global municipal solid waste (MSW) (Egan and Salmon, 2022).

As presented in Figure 12, standard PET fibre is classified as non-biodegradable according to common test methods used for testing plastics biodegradability in soil, compost by anaerobic digestion and seawater.

Common Test Method	Time	Biodegradable >70% biodegradation	Gray Zone	Semi-Biodegradable Moderate biodegradation	Nonbiodegradable <10% biodegradation
<b>SOIL</b> ASTM D5988-18	6 months (~180 days)	Cotton Flax	PBAT 30% degradation in 42 days	Wool Ramie	PET PLA
<b>COMPOST</b> ASTM D5338-18	45 days	PCL PLA		Cotton PBAT	PET
<b>ANAEROBIC DIGESTION</b> ASTM D5511-18	30 days	Cotton		PCL PLA	PET
<b>SEAWATER</b> ASTM D6691-17	90 days	PHBH	Cotton 49% degradation in 38 days	PCL PLA	PET

Figure 12. Textile fibre biodegradability according to standard test criteria for plastics (Egan and Salmon, 2022)

Different approaches have been studied and developed to improve PET biodegradation. One route to achieved this is by modification of PET in form of additives which can act as a starting point for degradation. As these components are added in to the polymerization mix the at the beginning stage of fibre-manufacturing process, the degradable regions of the fibres will be located throughout the fibre cross section and not only outside layer (a potential downside of biodegradation-enhancing surface finishes). The dispersion of degradable regions throughout the fibre allows better availability for both chemical and biological degradation when fibre is subjected to sufficiently optimal degradation conditions (Egan and Salmon, 2022).

This type of technology has already reached commercial maturity and one of its applications, called CiCLO® technology, has been made available by Intrinsic Advanced Materials. The

company website describes the technology as being designed to mitigate the negative effects of fugitive plastic microfiber pollution originating from synthetic textiles. The technology involves use of CiCLO<sup>®</sup> additive ingredient, designed to create ‘biodegradable spots’ in PES (or PA) polymer matrix, where naturally existing microbes can break down treated materials analogous to breakdown process with natural fibres (Intrinsic Advanced Materials LLC., 2025 a). Figure 13 demonstrates results from comparative study of biodegradation of standard PET microfibrils, poly(ethylene) (PE) microfibrils and cellulose microfibrils against CiCLO<sup>®</sup> additive treated PET microfibrils (Intrinsic Advanced Materials, LLC., 2025 b).

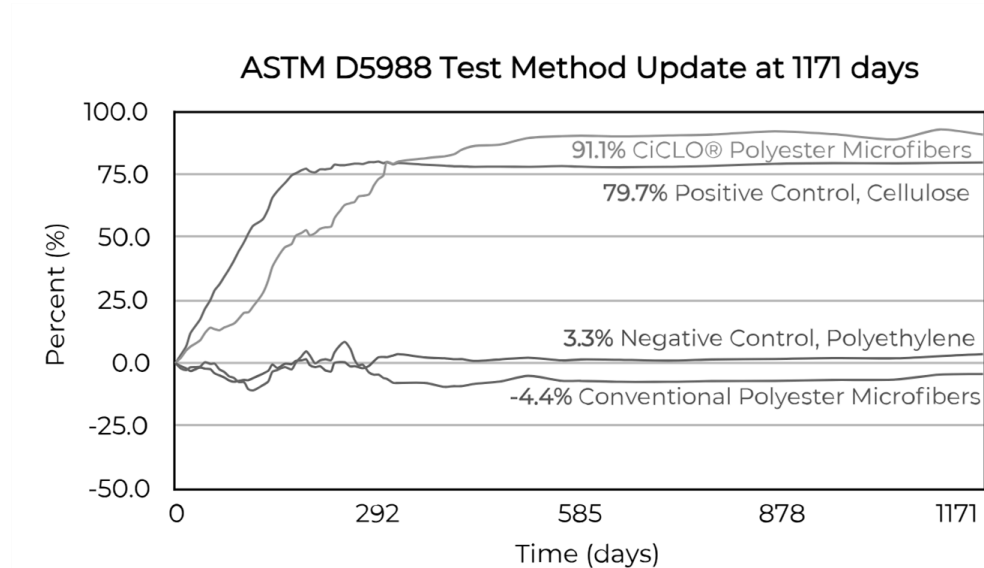


Figure 13. ASTM D5988 Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil – Comparison of CiCLO<sup>®</sup> PES Microfibers with standard PES microfibrils and cellulose biodegradation rates. (Intrinsic Advanced Materials, LLC., 2025

b)

Other approaches to improve PET biodegradation are the development of more complex aromatic-aliphatic co-PES options which are combinations of polymers where the introduction of aliphatic ester segments allows the polymer hydrolyze more easily (Egan and Salmon, 2022).

## 4 Textile adhesives

Regarding garment manufacturing technology, according to Petrie (2015), currently the most common method for joining apparel components together is by mechanical sewing or stitching. However, a range of alternative options are available (Figure 14). The use of adhesive bonding (along with thermal welding, also considered a subset of adhesive bonding) shows most prominence of the alternatives (Petrie 2015)

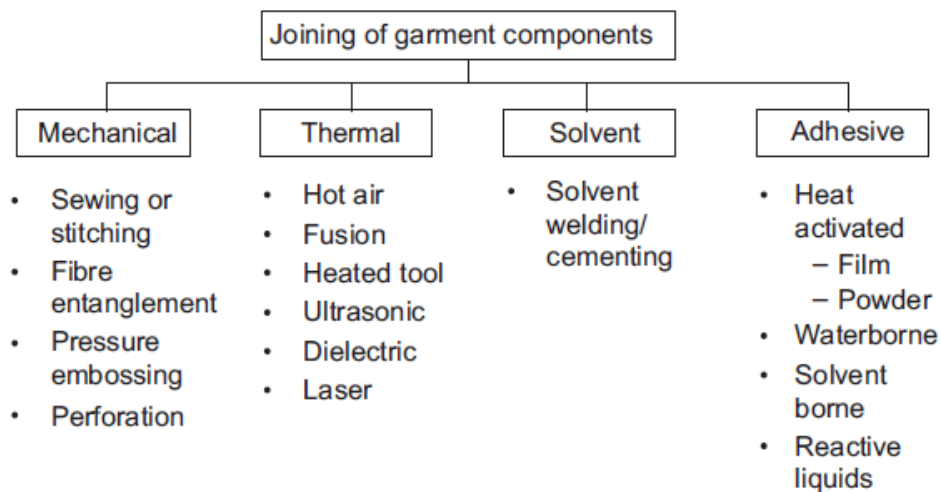


Figure 14. Joining of garment components (Petrie 2015)

Advantages of adhesive bonding as the method of choice include ability provide large stress bearing area, ability join all shapes and thicknesses, ability to join combinations of similar or dissimilar materials, possibly inexpensive and faster than other methods available. Disadvantages include possible need for special training as selection of bonding process to bring about optimal adhesion may be challenging and relates only to the intended application (Petrie 2015).

Like other adhesives, textile adhesives can be blended from different base polymers (they are often complex formulations of components including modifying substances e.g. tackifiers, inert fillers etc.) to produce specific end-properties within target overall cost.

Heat-activated textile adhesives have been formulated from various base polymers including styrene-butadiene, polyamide, polyurethane, poly(vinyl chloride), polyolefins and polyester.

Properties of polyester adhesives include their effective adhesion particularly to polyester fabrics and films, good water resistance and good solvent resistance.

Polyester adhesives are chemically related to the polyester fibre (Petrie 2015).

#### 4.1 Thermoplastic hotmelt adhesive films

With regards to various types of textile adhesives used, the heat activated thermoplastic hotmelt films, which harden by the cooling from the melt as opposed to from chemical reaction or solvent or waterloss, offer advantages due to their simplicity, relatively low energy demand/carbon footprint, ease of storage and relatively low waste generation. However, their use does require specialised application equipment and their application can cause heat damage on the substrate material. Their suitability also depends on the intended use as they have limited heat and chemical resistance (Petrie 2015).

## Experimental

The aim of the experimental part of this project was to explore options for creating new embellishment base layer(s) (in order to replace existing virgin PES textile surface and PU based support/backing and PU based adhesive layers) which would:

- i. withstand current embellishment manufacturing process conditions (processes which include sublimation printing, flock printing (optional), laser cutting)
- ii. pass subsequent product performance testing (e.g. testing based on Textiles - Domestic washing and drying procedures for textile testing (ISO 6330:2021), Textiles – Tests for colour fastness – Part C08: Colour fastness to domestic and commercial laundering (ISO 105-C08:2010), Tests for colour fastness – Part B02: Colour fastness to artificial light: Xenon arc fading lamp test (ISO 105-B02:2014), Tests for colour fastness – Part E01: Colour fastness to water (ISO 105-E01:2013), Tests for colour fastness – Part E04: Colour fastness to perspiration (ISO 105-E04:2013) according to customer specifications)
- iii. potentially improve sustainability rating (e.g. by using recycled raw material(s)), or enhance recyclability (e.g. by unification of base layer components by changing the backing/adhesive layers to compliment polyester textile) of the final embellishment product and, importantly, possibly compliment the sustainability rating of the garment/apparel which the embellishment is intended to be a part of (requests for use of recycled raw materials and monomaterial constructions originating from Elms Marketing customer-base).

The first part of the process was to source possible replacement for virgin PES textile quality with 100% recycled polyester (rPET) textile.

After preliminary evaluation of textile samples, two fabric options were selected for further assessment. PES backing/adhesive layers were also sourced and after preliminary evaluations (which include review of air-laid web adhesives and adhesive films of different thicknesses), two adhesive film options were selected for further assessment.

## 5 Materials and methods

### 5.1 Raw materials

Textile part of the base, 100% recycled polyester, rPET, (Global Recycled Standard, GRS certified (Textile Exchange, 2017)), OEKO-TEX® STANDARD 100 (OEKO-TEX Service GmbH, 2025 a) certifiable): 100% rPET woven twill (thickness 134  $\mu\text{m}$ , weight 113  $\text{g}/\text{m}^2$ , European supply), from here on referred to as *Twill fabric*, and 100% rPET knit satin (composition of 14% 150 denier (D) /72% 75D trilobal/14% 150D bright yarn, thickness 367  $\mu\text{m}$ , weight 239  $\text{g}/\text{m}^2$ , Asian supply), from here on referred to as *Satin fabric*, were selected.

For adhesive part of the base, two PES adhesive films, from here on referred to as *Adhesive 01* (transparent, thickness 40  $\mu\text{m}$ ) and *Adhesive 02* (opaque, white, thickness 112  $\mu\text{m}$ ), from two different European suppliers were chosen.

### 5.2 Fabric lamination – Laboratory scale

During factory embellishment manufacturing process, the laminated base fabric is sublimation dyed (in general, sublimation dye systems yield the best outcomes with polyester fabric due to types of dyes (disperse, nonionic) used and their compatibility with hydrophobic fibres (Stojanović et al., 2021)) with specified design. Sublimation process involves heat pressing of laminated fabric sheet at approx. 200 degrees Celsius ( $^{\circ}\text{C}$ ) for selected time and pressure. Given this already existing ‘heat press’ step in the manufacturing process, which the laminated fabric would have to go through, the standard production sublimation conditions, for both twill and satin type fabrics, were chosen as the starting point for manual lamination trials. It was found out, the laboratory scale fabric lamination (using sheet size of approx 50 cm x 65 cm for Satin fabric and 70 cm x 75 cm for Twill fabric) was possible to carry out simultaneously with the sublimation step.

First trials yielded unsatisfactory results for Twill fabric due to fabric dimensional change (DC), being too high  $>1.5\%$  (Appendix I) at conditions suitable for sublimation. After

consulting with the manufacturing mill, it was confirmed the fabric could be further heat stabilized by manufacturer and after this additional stabilization treatment by manufacturer, the fabric shrinkage was confirmed acceptable (Appendix II).

Suitable lamination/sublimation conditions were optimised using two different presses: SUBLI 1510+ large format oven for the Twill fabric and Insta 828 heat press for the Satin fabric.

With SUBLI 1510+ large format oven, sublimation conditions required optimisation for both Twill fabric/Adhesive 01 and Twill fabric/Adhesive 02 combinations for different reasons. Conditions were adjusted and option which yielded satisfactory results for both combinations was found (Appendix III).

No adjustment to standard sublimation conditions was required with Satin fabric/Adhesive 01 or Satin fabric/Adhesive 02 combinations on Insta 828 heat press.

After establishing suitable lamination/sublimation conditions for all four options (Twill fabric/Adhesive 01, Twill fabric/Adhesive 02, Satin fabric/Adhesive 01 and Satin fabric/Adhesive 02) DC on lamination/sublimation for all fabric/adhesive combinations was confirmed to be satisfactory (<1.5%) (Appendix IV).

### 5.3 Fabric lamination – Industrial scale

After preliminary performance testing, Twill fabric/Adhesive 02 combination was selected for 1<sup>st</sup> industrial scale (roll-to-roll) trial (carried out off-site by third party).

Laminated fabric was received back (from here after called *Twill/Ind trial* sample) for review and testing. Laminated fabric front and back appearance was considered satisfactory and after sublimation, *Twill/Ind trial* fabric DC was also confirmed satisfactory (Appendix V).

### 5.4 Sublimation printed fabric performance testing

After fabric/adhesive combination samples were sublimation printed and laser cut as per embellishment design. Cut samples were visually inspected for appearance (cut edge smoothness, no discoloration/burning) and once pass inspection, samples were applied onto

in-house testing PES fabric (using range of application conditions, APPENDIX VI) with SEFA DUPLEX PRO heat press for performance testing which include tests such as visual checks for embellishment adhesion, surface appearance, elasticity and measured checks for shrinkage before and after pre-determined set of wash cycles (following procedures based on standards such as *Textiles - Domestic washing and drying procedures for textile testing (ISO 6330:2021)* test variables (number of cycles, test temperatures etc.) set by customers; using instrumentation including Memmert conditioning chamber, VeriVide CAC 120 Color assessment cabinet, Grey Scale for assessing Change in Colour - ISO 105 A02, Grey Scale for assessing Staining - ISO 105 A03 Miele PW6065 professional wash machine, standardised James Heal Accudry<sup>2</sup> tumble drier.)

## 5.5 Sublimation and flock printed fabric performance testing

After sublimation printed only fabrics applied at higher temperature application conditions (170°C) passed performance testing (higher application temperature is required for flock printed embellishments), sublimated Twill fabric/Adhesive 02, Twill/Ind trial fabric, Satin fabric/Adhesive 01 and Satin fabric/Adhesive 02 sample sheets were also further printed with flock fibre and, after required curing process, laser cut to design.

Samples were further applied onto fabric and performance test was carried out in same manner as for sublimated only embellishments.

# 6 Results

## 6.1 Sublimation printed embellishments

Sublimated only products performance testing results are closely comparable with control product performance. However, maximum stretch (both ‘applied only’, or ‘washed’ samples)

for fabrics laminated with Adhesive 02 results in delamination (sharp corners/design tips lifting of the fabric). Also, washed embellishment *surface appearance* is affected by some degree of unravelling edges on all fabric/adhesive combinations tested.

The observed extent of unravelling on edges on the Twill fabric combinations may be considered acceptable to customer. The Satin fabric appearance was considered more problematic and focus was shifted to Twill fabric on the ‘sublimated only’ product option.

Intermittently (not seen with all sheets processed), slight curling of Twill fabric/Adhesive 02 was noted after cutting the product before it’s the application onto a fabric (Figure 15).



Figure 15. On the left, cut Twill fabric/Adhesive 02 presenting slight curl, on the right (flat) control product.

With Twill fabric/Adhesive 02, curling of the washed product was noted with larger area (> 3cm width) designs (Figure 16). Slight curling after wash can occur with the equivalent standard/control production materials. However, the slight curling noted with standard product is always in same (concave) direction. With the trial samples the curling observed could be either concave or convex, appearing randomly. Similar curling behaviour was noted with Twill/Ind trial fabric.



Figure 16. Twill/Ind trial samples after 5x 60degC wash and tumble dry cycles. Tumble dried samples present curling.

On further evaluations for Twill fabric/adhesive sublimated samples performance, when applied onto dark colored (dyed or sublimated fabric), twill fabric/Adhesive 02 was noted to be more opaque than the Twill fabric/Adhesive 01 option. This was attributed to the film thickness and the middle support/blocking layer present in the Adhesive 02 film.

Another difference between Adhesive 01 and Adhesive 02 on Twill fabric/sublimated only products was on the adhesion performance. With Adhesive 02, elasticity check on any design corner of 90 degrees or sharper (applied only or washed) would yield slight fabric corners lifting of the fabric (upto 1mm). With Adhesive 01, adhesion was seen to be better, even to the extent that upon maximum stretch of the substrate fabric, the substrate fabric would break before the bond between embellishment adhesive and fabric. Different application conditions (application of the embellishment onto substrate fabric) tested yielded same behaviour.

Colourfastness evaluations confirmed Twill fabric to have colourfastness comparable to control fabric.

## 6.2 Sublimation and flock printed embellishments

Sample sheets processed through additional flock printing process yielded mixed results. For Twill fabric products, some of the tested designs failed subsequent performance testing due to extensive curling during performance testing (observed with both Twill fabric/Adhesive 02, Twill/Ind trial fabric (Figure 17)).



Figure 17. Standard product (on the left) and Twill/Ind trial samples after 10x 60degC wash and tumble dry cycles. Twill/Ind trial samples present extensive curling after conditioning.

For Satin fabric products, Adhesive 01 option failed during flock printing process as the flock adhesive partially passed through laminated Satin. This was attributed to the more textured nature of the Satin fabric combined with the thinner adhesive resulting in weakened areas in adhesive film coverage. These weakened areas were unable withstand the pressure when subjected to print bead vacuum and adhesive was able to seep through.

No further testing was conducted on this combination.

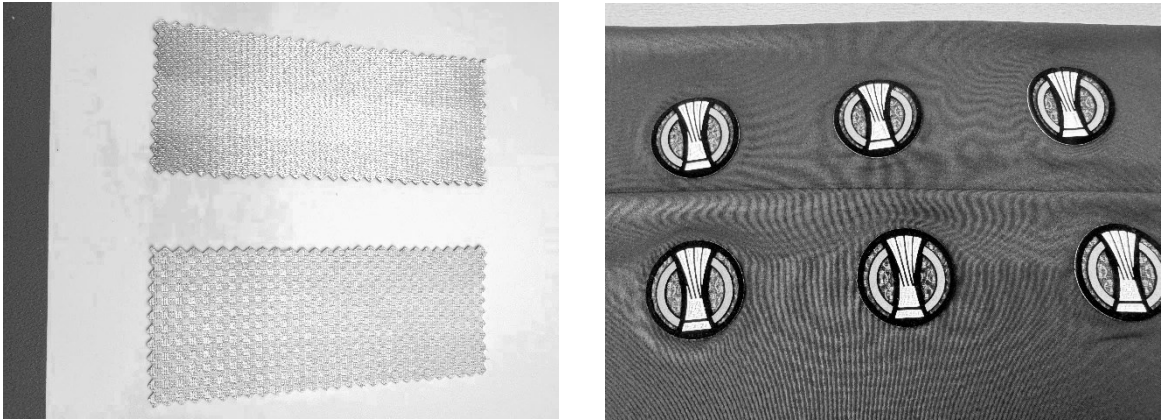


Figure 18. On the left: control satin (top) and trial Satin fabric/Adhesive 02 (bottom) applied onto sublimated fabric which shows through less on the trial satin. On the right: standard product (top) and trial Satin fabric/Adhesive 02 samples after 20x 60degC wash cycles.

Satin fabric/Adhesive 02 combination yielded better performance (the combination has passed multiple rounds of printing/performance testing and presents with better opacity than the control fabric/adhesive combination used (Figure 18). This option will continue to be trialled.

## 7 Discussion

Although the market share of recycled polyester fibre (rPET) of the total global polyester fibre market, has been reported as 13.6% in 2022 and 12.5% in 2023 (Textile Exchange, 2024 a) it turned out to be challenging to find suitable woven 100% rPET twill or satin type fabrics (before any consideration to cost of the material) for evaluation. This was due to most recycled-quality PET fabrics available on the market having some proportion of virgin PET or other non-PET (cotton, elastane etc) material included in their composition. The request for 100% rPET only textile fibre originates from Elms Marketing customer base and as outlined by Systemiq, supports sustainability goals necessary for the aim of significant reduction in greenhouse gases originating from PET. Also, although even less available currently, the preferred rPET option going-forward will be textile-to-textile recycled quality which will also reduce the quantities of PET fibre reaching landfill (Systemiq, 2023).

Reason for 100% rPET quality not being so widely available may originate from the requirements set by currently commonly used certifications in textile industry, which require minimum of 20% recycled fibre content for the use of the recycled label (Global Recycled Standard Textile Exchange, 2017; OEKO-TEX Service GmbH, 2025 b). The Asian fabric manufacturer was able to convert one satin option, previously only available with partially recycled content, to 100% rPET for evaluation (albeit on this occasion this quality was not selected for further assessment).

Once the potentially suitable fabrics were selected and after preliminary testing, additional heat stabilization of fabric by the twill fabric manufacturer was required.

White color of both recycled fabric options selected was acceptable for further processing.

Sourcing of suitable polyester textile adhesive film had its own challenges. Although polyester textile adhesives are available from number of sources, the actual composition of the film is usually described as polyester or co-polyester without further confirmation of the specific chemical composition and manufacturers are not forthcoming with details when enquired. FTIR scan and library search (Bruker Alpha ATR FTIR, APPENDIX VIII) conducted on both adhesive films selected matched both materials with PET as the first option. This can only be considered as indicative without further information from the

manufacturer. (Sample of PES adhesive film with 100% PET description and manufacturer confirmation about material recyclability is still awaiting to arrive). No recycled PES/PET textile adhesive film was found to be available yet. One manufacturer does offer recycled PET powder/PU composition. The *airlaid web* - type co-polyester adhesive films reviewed appeared not suitable due to much longer application times (laminated fabric onto garment fabric substrate) required.

With regards to polyester fabric, due to fibre labelling restriction on textile fibre labelled as polyester and with most fibre being manufactured comprising of PET (PES alternatives being more expensive and recycled quality mostly originating from waste PET bottles), it is easier to find PET only quality. The additional confirmation from manufacturers about fabrics were concerned with the % recycled content (% recycled content cannot be verified independently, supply chain certificates are required) which were readily available.

Optimization of sublimation processing conditions was required for the rPET twill combinations; standard sublimation processing conditions were suitable for rPET satin combinations. Although the sublimated product for twill constructions appears to perform acceptably for sublimated only product, further processing with flock printing onto sublimated twill was not successful as the flocked product fails performance testing due to observed curling. In contrast, the rPET satin type fabric in combination with adhesive 02 performs satisfactory after flock printing. The difference in performance may be due to difference in fabric thickness (the satin option being approx. three times thicker) and the thicker fabric resulting in more support/resistance against curling, or, the due to the thinner twill layer allowing flock adhesive to contact base adhesive layer and resulting in the changes observed. To establish the root cause and how to avoid the curling behaviour requires further investigation.

So far only the rPET twill fabric lamination has been trialled on industrial scale. The resulting laminated fabric has satisfactory appearance. Since, performance testing (of sublimated product only) revealed some quality issues. Further work to optimise industrial lamination will be carried out.

## 8 Conclusion

This project set out to explore alternatives to current embellishment products raw materials which would improve product sustainability and complement customers (apparel manufacturers) sustainability goals without having to make any significant changes to existing manufacturing processes.

Although it is evident from the literature review conducted, PET fibre is unlikely to become the 'green' option for textile industry anytime soon, increasing engagement in various fibre circularity enhancing practices, potential bio-based PET and PET alternatives (with same or better fibre performance) and approaches to address PET biodegradation (when applicable), there is scope for PET to become more sustainable version of itself in foreseeable future. Since there is no direct, more sustainable, replacement for the PET fibre quality in the volumes required to satisfy market demands, any effort to improve PET sustainability ought to be considered important and therefore aim to use recycled raw material(s) and raw material(s) which would unify PET based product construction were considered as reasonable options for the goal in mind.

This project serves as a starting point for further work. Although the trials carried out resulted in some positive outcomes (options Twill fabric/Adhesive 01, Twill fabric/Adhesive 02 and Satin fabric/Adhesive 02 did all show potential for different applications), optimisation work is required to either eliminate performance issues (e.g. curling, lack of opacity), or limit the final product design to options which do not present such issues. In any case, based on the outcome of trials carried out, it can be concluded the use of PET fabric combined with polyester adhesive(s) already available on the market appears to be feasible without major modifications to existing manufacturing process.

It is expected, more suitable recycled fabric options will become available in the market and it would be preferred to find rPET quality which originates from recycled PET textile fibre as opposed to recycled PET from food packaging industry. Possibilities for finding recycled PES/PET based adhesives will continue to be explored.

An important area of further work is to establish a sustainability rating for the product to allow the impact of raw materials change to be quantified. This would require co-operation

from materials supplier chain. Although polyester adhesives are chemically related to PET type polyester, whether the polyester adhesives trialled are suitable for mechanical PET fibre level recycling as they are (in combination with PET textile ‘substrate’ garments), remains an open question and needs more investigation. Compatibility with various chemical recycling options also needs to be verified.

Literature review highlighted materials/products labelling and traceability as an area where legislation updates for improved control and transparency would likely enhance textile industry’s ability in reaching its sustainability goals. Initiatives such as European digital product passport (DPP), of which stage-by-stage introduction for textile sector has been proposed to commence by 2027 (Legardeur and Ospital, 2024) and which is aimed to enable manufacturers (and consumers) to find the more sustainable options for any intended purpose and to allow better monitoring of textile materials flow in general, are welcomed.

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## APPENDICES

## APPENDIX I

Preliminary evaluations – Twill fabric %DC\* before heat stabilization by manufacturer.

Temperature, °C	Pressure, bar	Time, sec	Width, % DC	Length, % DC
187	2	30	-4.0%	-0.8%
187	2	63	-4.0%	-0.8%
187	1.5	63	-4.0%	-1.4%
187	1	63	-3.5%	-0.8%
177	1.5	63	-2.5%	-1.0%
177	1	63	-2.5%	-1.0%

\* - Direction indicates shrinkage

## APPENDIX II

Preliminary evaluations – Twill fabric %DC\* after heat stabilization by manufacturer.

Temperature, °C	Pressure, bar	Time, sec	Width, % DC	Length, % DC
187	2	63	-1.0%	-0.7%

\* - Direction indicates shrinkage

## APPENDIX III

Fabric lamination - SUBLI 1510+ large format oven – optimisation.

Temperature, °C	Pressure, bar	Time, sec	Twill fabric/Adhesive 01	Twill fabric/Adhesive 02
210	4	80	Blurry print image	Adhesive seeps through fabric front
210	4	55	Sublimated fabric front: Appearance satisfactory Laminated fabric back: Appearance satisfactory	Adhesive seeps through fabric front
210	3	55	Sublimated fabric front: Appearance satisfactory Laminated fabric back: Appearance satisfactory	Sublimated fabric front: Appearance satisfactory Laminated fabric back: Appearance satisfactory

210	2	55	Adhesive delamination	Adhesive delamination
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## APPENDIX IV

Fabric/adhesive combinations %DC\* after lamination conditions optimisation.

Heat Press	Lamination conditions, °C/bar/sec	Combination	Width, % DC	Length, % DC
Insta 828	187/2/63	Satin fabric/Adhesive 01	-0.5%	-0.6%
	187/2/63	Satin fabric/Adhesive 02		
SUBLI 1510+	210/3/55	Twill fabric/Adhesive 01	-0.7%	-0.4%
	210/3/55	Twill fabric/Adhesive 02	-0.7%	-0.6%

\* - Direction indicates shrinkage

## APPENDIX V

Industrial lamination trial, Twill fabric/Adhesive 02 combination, %DC\* on sublimation.

Heat Press	Lamination conditions, °C/bar/sec	Combination	Width, % DC	Length, % DC
SUBLI 1510+	210/3/55	Twill/Ind trial	-0.9%	-0.5%

\* - Direction indicates shrinkage

## APPENDIX VI

Application (embellishment onto fabric) conditions - SEFA DUPLEX PRO heat press

Temperature, °C	Pressure, bar	Time, sec
150	15	4
160	20	3
160	25	4
170	20	3

## APPENDIX VII

## Performance testing results tables - Examples

<i>Wash Tests – Reference method: Textiles - Domestic washing and drying procedures for textile testing (ISO 6330:2021)</i>				
	<b>Twill fabric/ Adhesive 01 – Sublimation printed</b>		<b>Twill fabric/ Adhesive 02 - Sublimation printed</b>	
Application conditions (embellishment to fabric), °C/bar/sec	10x 60°C wash cycles	15x 60°C wash and tumble dry cycles	10x 60°C wash cycles	15x 60°C wash and tumble dry cycles
150-15-4	PASS	PASS	PASS	PASS
160-20-4	PASS	PASS	PASS	PASS
160-25-4	PASS	PASS	PASS	PASS
170-20-3	PASS	PASS	PASS	PASS
PASS for Evaluation for Surface Appearance, Adherence, Colour change, Elasticity				

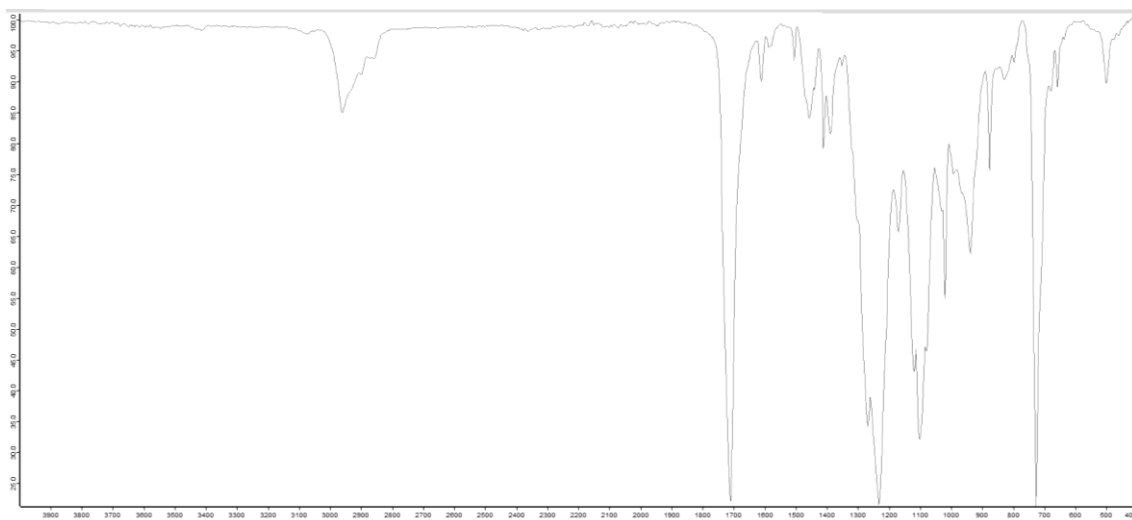
<i>Wash Tests – Reference method: Textiles - Domestic washing and drying procedures for textile testing (ISO 6330:2021)</i>				
	<b>Satin fabric/ Adhesive 01 – Sublimation and flock printed</b>		<b>Satin fabric/ Adhesive 01 – Sublimation and flock printed</b>	
Application conditions (embellishment to fabric), °C/bar/sec	10x 60°C wash cycles	15x 60°C wash and tumble dry cycles	20x 60°C wash cycles	20x 60°C wash and tumble dry cycles
170-20-3	N/A	N/A	PASS	PASS
PASS for Evaluation for Surface Appearance, Adherence, Colour change, Elasticity				

Tests for colour fastness – Twill fabric comparison with Internal control			
	Adjacent fibre	Twill fabric GC Color Change	Internal Control fabric GC Color Change
Tests for colour fastness – Part E01: Colour fastness to water (ISO 105-E01:2013)	Acetate	4	4
	Cotton	4	4/5
	Nylon	4	4
	Polyester	4/5	4/5
	Acrylic	4/5	4/5
	Wool	4/5	4
Tests for colour fastness – Part E04: Colour fastness to perspiration (ISO 105-E04:2013) - Alkaline	Acetate	5	4
	Cotton	5	4
	Nylon	4	3/4
	Polyester	5	4
	Acrylic	5	5
	Wool	5	4/5
	Acetate	5	4

Tests for colour fastness – Part E04: Colour fastness to perspiration (ISO 105-E04:2013) - Acid	Cotton	5	4/5
	Nylon	5	4/5
	Polyester	4	4/5
	Acrylic	5	5
	Wool	4/5	5

## APPENDIX VIII

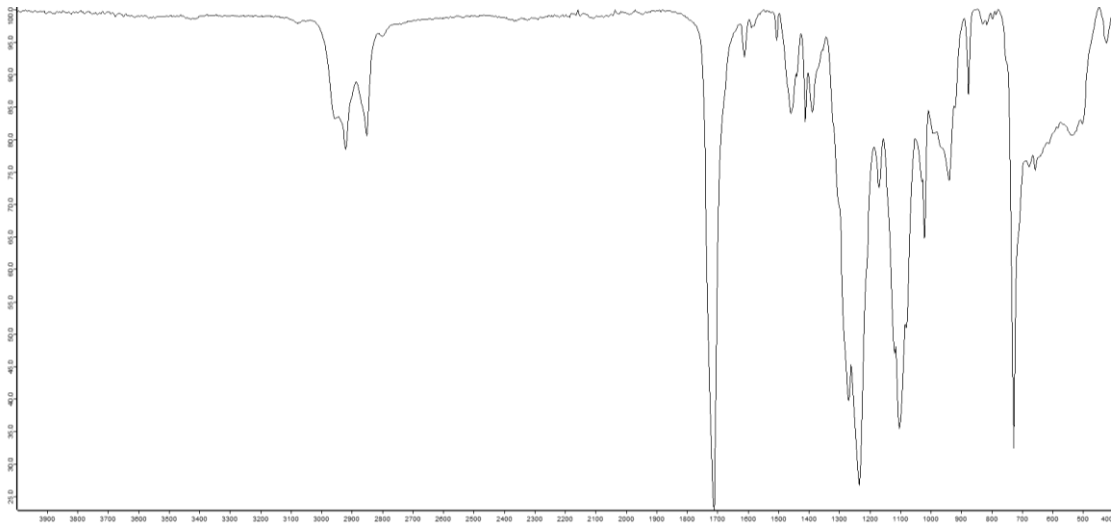
### FTIR Spectrum of Adhesive 01



### Adhesive 01 spectrum library search result:

Hit No.	Color	Hit Quality	Compound Name	CAS number	Molecular formula	Molecular weight
1	<input checked="" type="checkbox"/>	621	POLYESTER, TEREPHTHALIC ACID BASED, B...			
2	<input type="checkbox"/>	594	POLYESTER, TEREPHTHALIC ACID BASED, B...			
3	<input type="checkbox"/>	583	POLY(ETHYLENE TEREPHTHALATE)	29154-49-2	$(-COC_6H_4COOCH_2CH_2)_n$	

### FTIR Spectrum of Adhesive 02



Adhesive 02 spectrum library search result:

Hit No.	Color	Hit Quality	Compound Name	CAS number	Molecular formula	Molecular weight
1	<input checked="" type="checkbox"/>	680	POLYESTER, TEREPHTHALIC ACID BASED, BIODEGRADABLE			
2	<input type="checkbox"/>	644	KODEL, POLYESTER FIBER			
3	<input type="checkbox"/>	620	SENSURA			

Comparison of materials FTIR Spectra

